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EXECUTIVE SUMMARY

Testing of immersion suits is conducted in calm or circulatory water. Several investigators have argued that this is an unrealistic test for a suit that is designed to protect a human from hypothermia in open ocean conditions. The present study was designed to investigate the effect of standard wave conditions (0 to 70 cm) on dry immersion suit insulation when tested on humans and a manikin simultaneously. The objectives of the study were 1) to see if the thermal insulation of suits used on a manikin and humans are equally affected by wave motion; and 2) to define which component of the suit is most affected by the wave motion. Six human subjects and a thermal manikin dressed with the same dry immersion suit system were immersed simultaneously for one hour in 16°C water rendered turbulent with irregular waves. One immersion was performed for each randomly chosen wave condition, from 0 to 70 cm wave height, changing by steps of 10 cm. Rectal and skin temperature (12 sites), in addition to skin heat loss (12 sites) and heart rate were continuously monitored on humans during the immersions. In addition, air and water temperatures, and heat fluxes and surface temperatures were measured at 12 sites on the subjects and manikin for each compartment of the dry suit system (skin, pile garment, suit garment). This allowed the calculation of the thermal resistance of every suit compartment in addition to the air and water boundary layer surrounding the suit in order to define which suit compartment has its insulation significantly affected by the wave motion. The results showed that none of the physiological parameters were significantly affected by the wave conditions, except for the skin heat flux which increased with wave height by 19%. The thermal resistance data showed that wave height up to 70 cm decreased dry suit system insulation by 14 % and 17% when measured on human subjects and manikin, respectively, and that the only suit component significantly affected by the wave motion was the insulation of the water and air boundary layers surrounding the body. The body sites that were the most affected by the effect of wave motion were the head, and the proximal limbs with a 58% and 63% decrement in suit thermal resistance from 0 to 70 cm wave height for humans and manikin, respectively. Total suit insulation values were on average 46% lower when measured on the manikin compared to human subjects for the same water conditions and suit system. The discrepancy can largely be explained by differences in buoyancy and amount of trapped air in the suit between the manikin and human subjects. It is recommended that the flotation characteristics and the standards for manikin testing be improved to reflect more closely the flotation and thermal physiology of humans. Those data can help in the development of better immersion suits for the CF and can be implemented in a model for prediction of survival time in cold water.

ABSTRACT

The objective of the present study was to investigate the effect of standard wave conditions (0 to 70 cm) on dry immersion suit insulation when tested on humans and a manikin simultaneously. Six human subjects and a thermal manikin dressed with the same dry immersion suit system (pile undergarment insulation, uninsulated immersion suit and neoprene gloves and hood) were immersed simultaneously for one hour in 16°C water rendered turbulent with an irregular wave pattern. One immersion was performed for each randomly chosen wave condition, from 0 to 70 cm wave height, changing by steps of 10 cm. In addition to the physiological parameters measured on the human subjects (skin and rectal temperatures, skin heat loss and heart rate), and the ambient temperature of water and air, heat fluxes and surface temperatures were measured at 12 sites on the subjects and manikin for each compartment of the dry suit system (skin, pile garment, suit garment). This allowed the calculation of the thermal resistance of every suit compartment in addition to the air and water boundary layer surrounding the suit. The results showed that none of the physiological parameters were significantly affected by the wave conditions, except for the skin heat flux which increased with wave height from 72.0 ± 1.9 W • m^{-2} at 0 cm to 85.5 ± 2.9 W • m^{-2} at 70 cm. The thermal resistance data showed that wave height up to 70 cm decreased dry suit system insulation by 14 and 17% when measured on human subjects and manikin, respectively, and that the only suit component significantly affected by the wave motion was the insulation of the water and air boundary layers surrounding the body. The body sites that were the most affected by the effect of wave motion were the head, and the proximal limbs with a 58% and 63% decrement in suit thermal resistance from 0 to 70 cm wave height for humans and manikin, respectively. Total suit insulation values were on average 46% lower when measured on manikin [average of 0.68 ± 0.01 Clo (0.105 ± 0.002 m^2 • K • W^{-1})] compared to human subjects [average of 1.25 ± 0.03 Clo (0.194 ± 0.005 m^2 • K • W^{-1})] for the same water conditions and suit system. The discrepancy can largely be explained by differences in buoyancy and amount of trapped air in the suit between the manikin and human subjects.

INTRODUCTION

The concept of an immersion suit to protect humans in cold water is not new. There are samples of Eskimo exposure suits in the Danish National Museum that are over 100 years old. However, loss of life from shipwreck or falling over the ship's side for whatever reason has always been accepted as an occupational hazard for mariners (Nicholl, 1960). In the days of 'pressing' sailors into service, the idea of providing an item of life support equipment such as a life-jacket or immersion suit to save a life was not accepted because first, the equipment cost money and second, it might aid the sailor to make good his escape from pressed service.

It is not until the beginning of the 20th Century that more emancipated views started to be considered and any serious ideas of immersion suits were developed. The causes of loss of life from immersion in cold water, however, were still poorly understood. More often than not the death certificates simply recorded "died from exposure" and or "drowning". The concept of cold shock and hypothermia was ill-understood. It wasn't until 1946, when the Talbot Committee (Talbot Committee, 1946) reported that between 30-40,000 officers and enlisted men died in the Second World War from drowning and cold, that attention was finally drawn to the problem. This was further supported by McCance et al. (1956) who examined these cases in more detail and published their findings in 1956.

It then became apparent that sudden immersion in cold water was a life-threatening situation (Glaser and Hervey, 1951) and some form of suit, preferably a dry suit should be worn for protection following ship abandonment. Until post-World War II no standards existed for such an item. It wasn't until 1984 that the first international standard was produced by the IMO (International Maritime Organization, 1984). Driven by the offshore oil industry, the Western World have started to introduce their own national standards for helicopter air crew, oil rig workers, fishermen and for general ship's company (Canadian General Standards Board, 1988; 1989a; 1989b). All of the testing of immersion suits, however, is conducted either in calm or circulatory water, the circulation of the water intended to stir up the boundary layer around the suit (the water is stirred by means of bubbling compressed air through the tank).

Several investigators have argued that this is an unrealistic test for a suit that is designed to protect a human from hypothermia in open ocean conditions where waves of 5-8 meters can easily be expected. In support of this argument, Steinman et al. demonstrated that the core cooling rate and the declines in skin temperature of human subjects were significantly larger in rough water than in calm water. Such differences were found for

loose-fitting wet suits but not for tight-fitting wet suits or dry suits (Steinman et, 1987). Later, Romet et al. (Romet et al., 1991) confirmed the Steinman study by reporting a significant reduction of wet immersion suit insulation in turbulent water conditions when compared to still water by an average of 29.7% when measured on humans. When measured on a thermal manikin, they found a reduction of 55.9%. It was found that the manikin consistently overestimated this decrement in insulation when compared to humans. Recently, Sowood et al. (Sowood et al., 1994) reported a reduction of insulation, this time for dry immersion suits by about 30% in turbulent water (wave height of 60 cm) compared to still water when tested on a manikin. Despite the evidence of a decrement in wet immersion suit insulation in turbulent water for both manikin and humans, the effect of wave motion on dry immersion suit insulation has been studied only on manikins and for non-standardized wave conditions.

The objective of the present study was to investigate the effect of standard (or controlled) wave conditions (0 to 70 cm) on dry immersion suit insulation when tested on humans and a manikin simultaneously. A second objective was to define which part of the dry immersion suit system was most affected by the wave motion. It was hypothesized that suit thermal resistance would be affected by the wave motion, that the major decrement in thermal resistance will be observed at the water/air boundary layer, and that the observed decrement for human testing will be less than the one previously reported during manikin testing.

MATERIAL AND METHODS

Subjects. Six healthy male subjects volunteered to participate in the study. The anthropometric characteristics of the subjects are presented in Table 1. The percentage of body fat was estimated from the summation of five skinfold thicknesses (sternum, sub-scapular, anterior thigh, posterior calf) measured by a Harpenden skinfold caliper (British Indicator, England) and calculated using the relationship developed by Katch et al. (1979). The health status of all subjects was assessed by a medical authority. The subjects were fully informed of the procedures and possible risks of the study and their right to withdraw from the experiment at any time without prejudice. Written informed consent was obtained from all subjects before experimentation. The protocol was approved by Institutional Ethics Committees.

The subjects were asked to abstain from smoking and using any medication, drug, or other stimulant (including caffeine and alcohol) for at least 12 h before the experiments.

All experiments were performed at the same time of the day for each subject. The tests were carried out in the Clear Water Towing Tank (CWTT) of the National Research Council's Institute for Marine Dynamics (IMD) in St-John's, Newfoundland.

Manikin. Parallel to the human tests, the immersion suits were also tested using a thermal manikin (Thermal Instrumented Manikin, TIM, CORD Group Limited, Dartmouth, Nova Scotia) immersed in the same water conditions as for the subjects' immersions. The manikin was immersed at the same time at the other side of the carriage (about 6 m away from the subject) without interfering with the subject or changing the wave pattern. The probe locations (except for the location of the heat flux transducers, see below) and the clothing were the same as for the human subjects.

Temperature, heat flow and heart rate measurements. Core temperature of the subjects was estimated by measuring rectal temperature (T_{re}) using a 2 kohm thermistor (YSI model 44004, Yellow Spring, OH, U.S.A.) inserted 15 cm into the rectum. Heart rate (HR) was measured using a three point leads system (Multicare 304, Rigel research Ltd, Surrey, England). Skin temperature (T_{sk}) using 6 kohm thermistors (YSI model 44018, integrated into the heat flux transducers) and skin heat loss (H_{sk}) using heat flux transducers (HFTs, Concept Engineering, Old Saybrook, CT) were measured on 12 sites

Table 1. Anthropometric characteristics of the subjects

Subject #	Age, yr	Height, cm	Weight, kg	A_D m^2	Body fat %
1	23.1	178	75.2	1.92	10.6
2	22.2	179	78.5	1.97	14.4
3	25.6	179	76.0	1.94	22.3
4	21.2	183	79.9	2.01	18.3
5	25.2	178	79.5	1.97	18.4
6	32.5	179	69.6	1.87	11.4
mean ± SE	25.0 ± 1.7	179 ± 1	76.5 ± 1.6	1.95 ± 0.02	15.9 ± 1.9

A_D, DuBois surface area (Dubois and Dubois, 1916).

based on the Hardy and Dubois modified 12 points system (Olesen, 1984). The mean $T_{ski}(\overline{T}_{sk})$ and mean H_{sk} ($\overline{H}_{sk}$) were calculated using the 12 site modified weighting

system of Hardy and Dubois. The measurement sites (with the weighting factors) were as follows: forehead (0.07), right scapula (0.088), left upper chest (0.088), right abdomen (0.088), left lower back (0.088), right anterior thigh (0.095), left posterior thigh (0.095), right shin (0.065), left calf (0.065), left shoulder (0.046), left upper arm (0.046), and left forearm (0.046). The difference between the modified Hardy and Dubois weighting system (Olensen, 1984) and ours is in the coverage of the extremities and upper limbs. For our 12 site system, the extremities (feet and hands) were not used as measurement sites for the calculation of the suit system resistance because they do not contribute significantly (being vasoconstricted) to the survival of individuals immersed in cold water. Instead, two additional sites (shoulder and forearm) were added to the upper limbs which were divided into three segments: shoulder, upper arm and forearm. The same 12 point system was used on humans and on the manikin, except that the HFTs were fixed on the pile garment of the manikin (the insulative garment used under the immersion suit; see below for detailed description) instead of the skin as it was for the humans. The skin temperatures of the manikin were measured by 2 kohm thermistors (YSI model 44004, Yellow Spring, OH, U.S.A.) fixed on the aluminum skin of the manikin. The HFTs were fixed on the pile garment of the manikin to avoid applying a large correction factor to the heat flow values due to the high thermal conductivity of the aluminum skin of the manikin relative to the thermal conductivity of the HFTs (see Ducharme et al.). At thermal steady state, the heat flow values (in W) should be independent of the location of the sensors inside the suit system along the same flow path. The heat flux values (in $W \cdot m^{-2}$), however, are affected by the location of the sensors in the suit system because they are dependent on the surface area (SA) of the body site they represent. Because the body site SA increases when measured over the close fitting pile garment compared to the skin because of the pile thickness (6 mm), the heat flux values have to be corrected by a factor proportional to the SA ratio as follows:

$$\text{correcting factor}_{\text{site}} = SA_{pile}/SA_{sk}$$

where SA_{pile} and SA_{sk} are the surface area (in m^2) of the body site over the pile garment and at the skin, respectively. Since all body sites, except for the head, can be represented by a cylinder (Wissler, 1970), then the SA ratio for those sites can be simplified as follows:

$$SA_{pile}/SA_{sk} = 2\pi \cdot r_{pile} \cdot h \,/\, 2\pi \cdot r_{sk} \cdot h = r_{pile} \,/\, r_{sk}$$

$$= 2\pi \cdot Circ_{pile} \,/\, 2\pi \cdot Circ_{sk} = Circ_{pile} \,/\, Circ_{sk}$$

where $Circ_{pile}$ and $Circ_{sk}$ are the body site circumferences (in m) at the sensor location over the pile garment and at the skin, respectively. For the head site, the correcting factor can be defined as follows:

$$\text{correcting factor}_{\text{head}} = 4\pi \cdot r^2_{pile} / 4\pi \cdot r^2_{sk} = Circ^2_{pile} / Circ^2_{sk}$$

It should be noted that the correction factor is simply a geometric projection of what the heat flux at the skin would be to give the observed heat flux at the measurement site.

In addition to skin temperatures and heat flow measurements, two other sets of 12 thermistors were fixed on the surface of the pile garment (measured by the integrated thermistors on the HFTs for the manikin) and on the outside surface of the immersion suit (see Fig. 1) for the same sites on the body. The mean temperature of the pile garment and of the suit were measured the same way as for $\overline{T}_{sk}$. The HFTs were recalibrated according to the method of Ducharme et al. (Ducharme et al., 1990) and the heat flow values were corrected to account for the thermal insulation of the HFTs (Ducharme et al., 1990). All measurements of temperatures, heat flows and heart rate were performed continuously during the immersion period using a computer-controlled data acquisition system (Hewlett Packard, model HP 75000 series 8) and averaged over a 1 minute period.

Measurement of insulation. The thermistor arrangement on the humans and on the manikin creates a system of three layers (components of the suit system) capable of measuring the insulation of the pile garment (including the air layer between the skin and the pile; R_{pile} in Clo), the suit (including the air layer between the pile garment and the suit; R_{suit} in Clo), and the water/air layer ($R_{water/air}$ in Clo; see Fig. 2) for every site as follows:

$$R_{pile} = (\Delta T_1/H) / 0.155$$
$$R_{suit} = (\Delta T_2/H) / 0.155$$
$$R_{water/air} = (\Delta T_3/H) / 0.155$$

where ΔT_1(°C) = T_{sk} - T_{pile}, ΔT_2 (°C) = T_{pile} - T_{suit}, ΔT_3 (°C) = T_{suit} - $T_{water/air}$, H is the heat flow in $W \cdot m^{-2}$ measured by the HFTs, and 0.155 is the conversion factor from $m^2 \cdot K \cdot W^{-1}$ to Clo. The resistance of the suit system components for the whole body (in Clo) was calculated as follows:

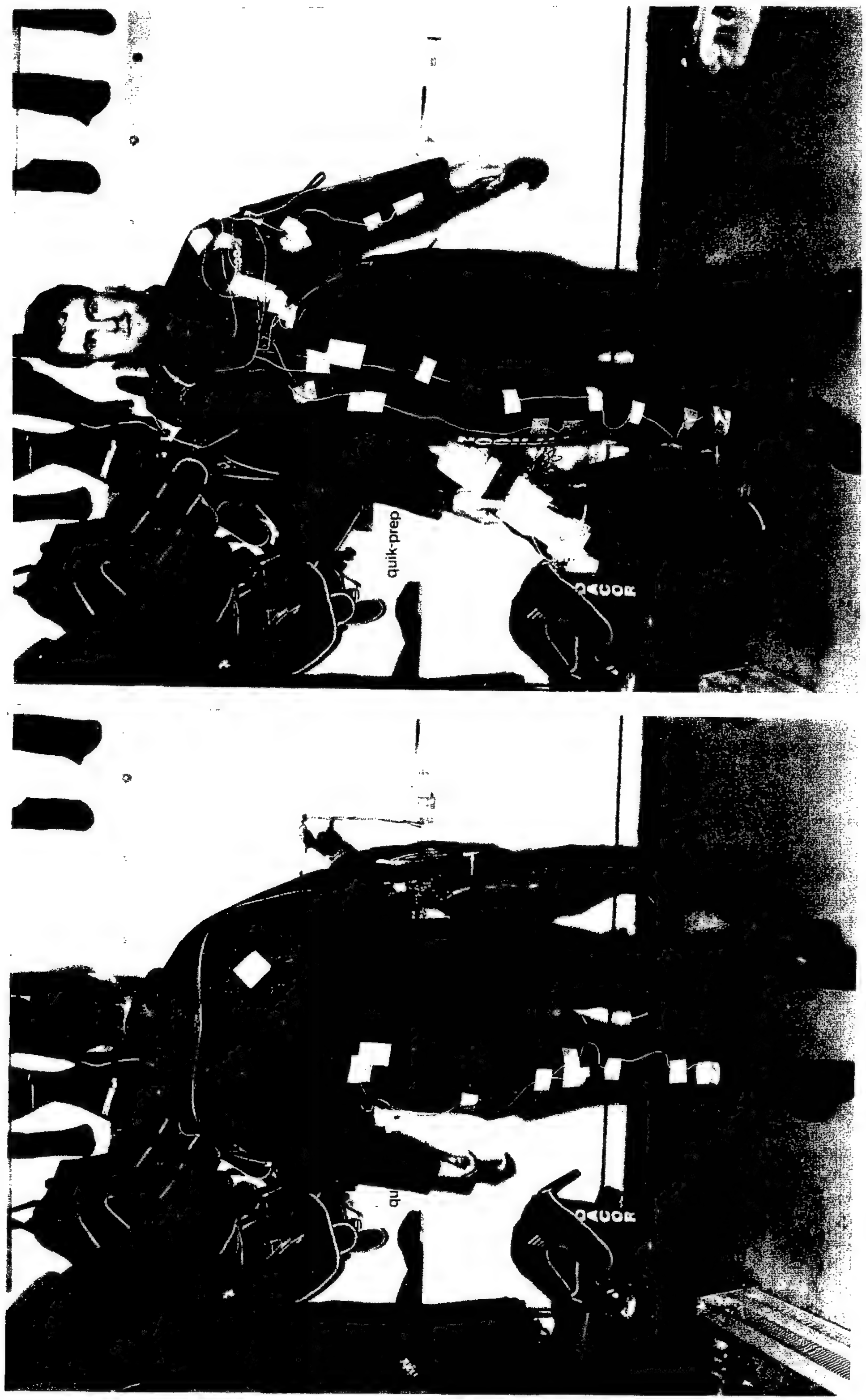

Figure 1. Pictures showing the outside surface of the immersion suit and the positioning of the temperature sensors.

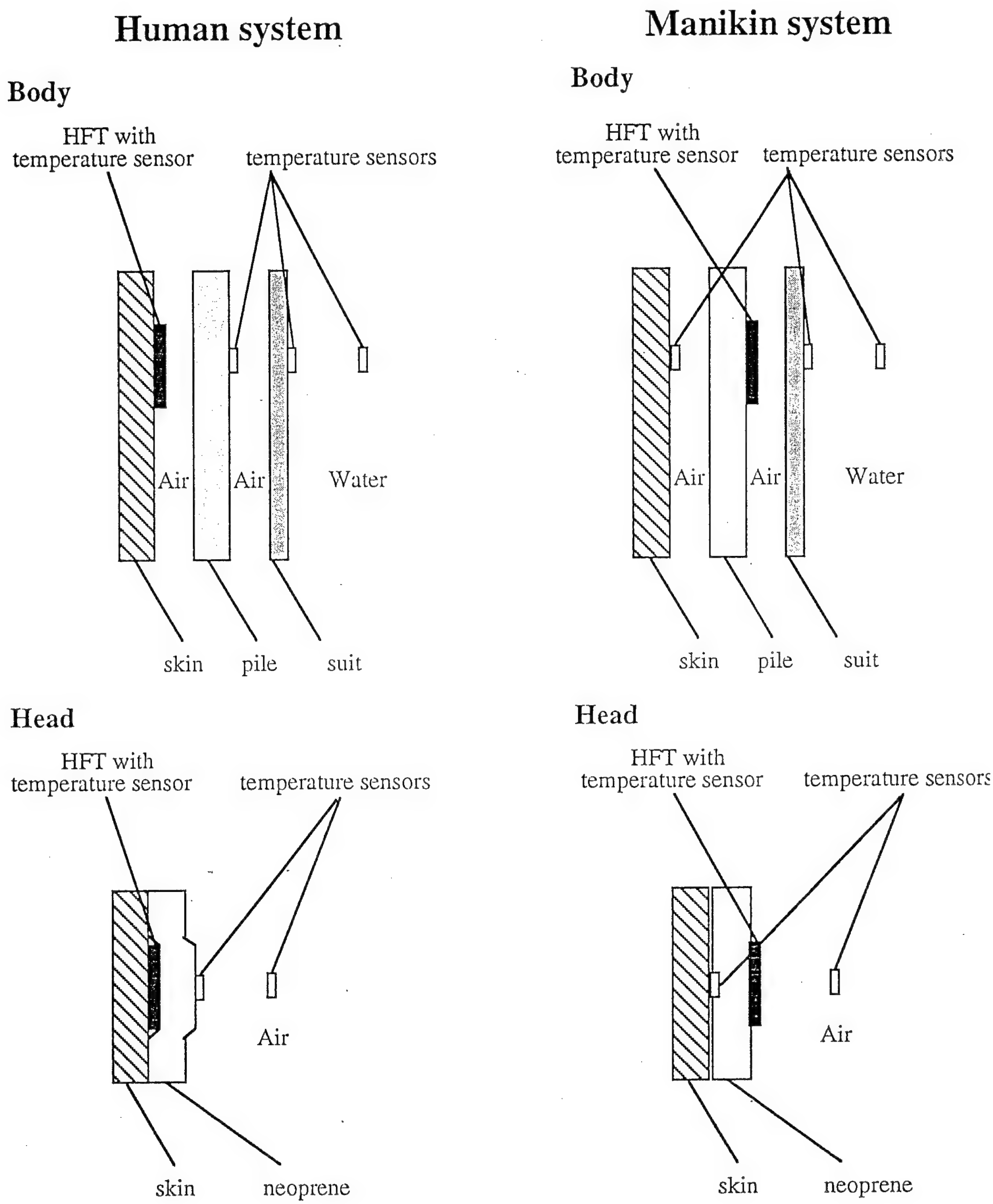

Figure 2. Schematic representation of the temperature and heat flux sensors arrangements inside the dry immersion suit system used on human subjects and the manikin during the trials.

$R_{pile}\ body = (\sum A_i / A_{body} \bullet \Delta T_{1i}) / (\sum A_i / A_{body} \bullet H_i) / 0.155$
$R_{suit}\ body = (\sum A_i / A_{body} \bullet \Delta T_{2i}) / (\sum A_i / A_{body} \bullet H_i) / 0.155$
$R_{water/air}\ body = (\sum A_i / A_{body} \bullet \Delta T_{3i}) / (\sum Ai / A_{body} \bullet H_i) / 0.155$

where i represents the body sites from 1 to 12, A_i / A_{body} represents the ratio of the site "i" surface area (in m^2) over the body surface area (in m^2) and is equivalent to the weighting factor of site "i" used to measure $\overline{T}_{sk}$ The 12 body sites represent a resistance system in parallel (see Appendix for mathematical development of the formulae). The total suit system resistance for the whole body was measured as follows:

$R_{total}\ body = R_{pile} + R_{suit} + R_{water/air}$

where the three components of the suit system represent a resistance system in series.

Calculation of R_{total} CORD-DCIEM weighted. R_{total} was obtained for the manikin' suit system by the CORD Group using the temperature sensors imbedded into the manikin' skin and the manikin power source (CORD Group Limited, 1994). To calculate R_{total}, CORD Group used the data from 13 segments on the manikin including both hands and feet, and used water temperature as an indicator of ambient temperature for all sites. In the present study, R_{total} was calculated for the manikin using 12 sites excluding the hands and feet, and using air temperature as the ambient temperature for the forehead site. To make a more valid comparison between our manikin resistance data and CORD Group data, the CORD Group R_{total} data were recalculated (R_{total} CORD-DCIEM weighted) from the original skin temperature and power results obtained from the manikin during the immersions at different wave conditions (CORD Group Limited, 1994) and using the following equations for uniform skin temperature (see *APPENDIX* for details):

$$1/R_{total} = \sum 1/ R_i \bullet \partial_i$$

$$R_i = [(T_{sk} - T_{amb}) \bullet A_i]/P_i$$

where R_i is the total thermal resistance at the site i (in $m^2 \bullet K \bullet W^{-1}$), ∂i is the weighting factor for site i used in the present study, T_{sk} is the skin temperature of the manikin at the site i (in °C), T_{amb} is the ambient temperature for the site i (in °C), A_i is the surface area of the manikin' segment represented by site i (see McKenna and Simoes Ré, 1995), and P_i is the power provided to the site i of the manikin to maintain the skin temperature constant (in W).

The ambient temperature was continuously monitored by four 2 kohm thermistors (YSI, model 44004, Yellow Spring, OH, U.S.A.): three of them were located in water within 10 cm from the feet of the subjects, and a fourth one measuring air temperature was located about 1 meter above the subject. The different insulation values were calculated at steady-state during the water immersion from an average of temperature and heat flow data for the last 15 minutes of the 1h immersion.

Experimental procedures. On their first visit to the Institute, the subjects were familiarized with the equipment and the procedures that were used during the wave tests. They experienced a 30-min immersion in water at 16°C with waves set at a height of 40 cm while being fully instrumented and wearing the same clothing as during the wave tests. Thereafter, the subjects were immersed once a day for nine consecutive days in water at 16°C for one hour. Before the immersion, the subjects were instrumented with 1) a disposable and sterile rectal probe, 2) ECG leads for continuous cardiac monitoring, 3) and 12 heat flow transducers (incorporating temperature sensors). The subjects were then dressed with a one-piece undergarment (Helly Hansen pile underwear, model F456), a set of pile socks (Helly Hansen pile socks, model F454), an uninsulated Typhoon Ranger dry immersion suit (nylon/butyl laminate with neck and wrist latex/rubber seals and a back entry waterproof zipper; Typhoon International Limited, London, U.K.) modified in the chest to accept monitoring wires (a 3 m waterproof umbilical was sealed to the suit to allow the sensor leads to be led from inside the suit to the data acquisition equipment), 3 mm neoprene three-finger diver's mitts, a 3 mm neoprene diver's hood with chin strap, and an inflatable twin lobe life vest with 15.4 kg of buoyancy (model MD 1141, Mustang Ind. Inc, Richmond, B.C.). An additional set of 12 thermistors was fixed on each of the six pile garments and suits that were being used by the six subjects (the same suit system was used by a subject for every wave conditions). The locations of the sensors on pile garments and suits were the same as for the measurement of skin temperatures, and the sensors stayed on the suit components during the whole duration of the experiment.

The subjects, assisted by a diver, entered the water via a platform suspended just above the water surface. Once in the water, the subjects were towed out to the centre of the tank using a pulley system operated from the platform. Once in position, the subjects' feet were hooked with flexible positioning cable onto a cord fixed across the tank to ensure a constant positioning of the subjects relative to the wave propagation (facing them) and relative to the carriage where data collection was being done (see Fig. 3). The flexible positioning cables ensured that while the subjects were not drifting from the test area, they were maintaining freedom of movement. The wave heights were chosen randomly and varied between 0 and 70 cm (WH0 to WH70) by steps of 10 cm. The JONSWAP (Joint

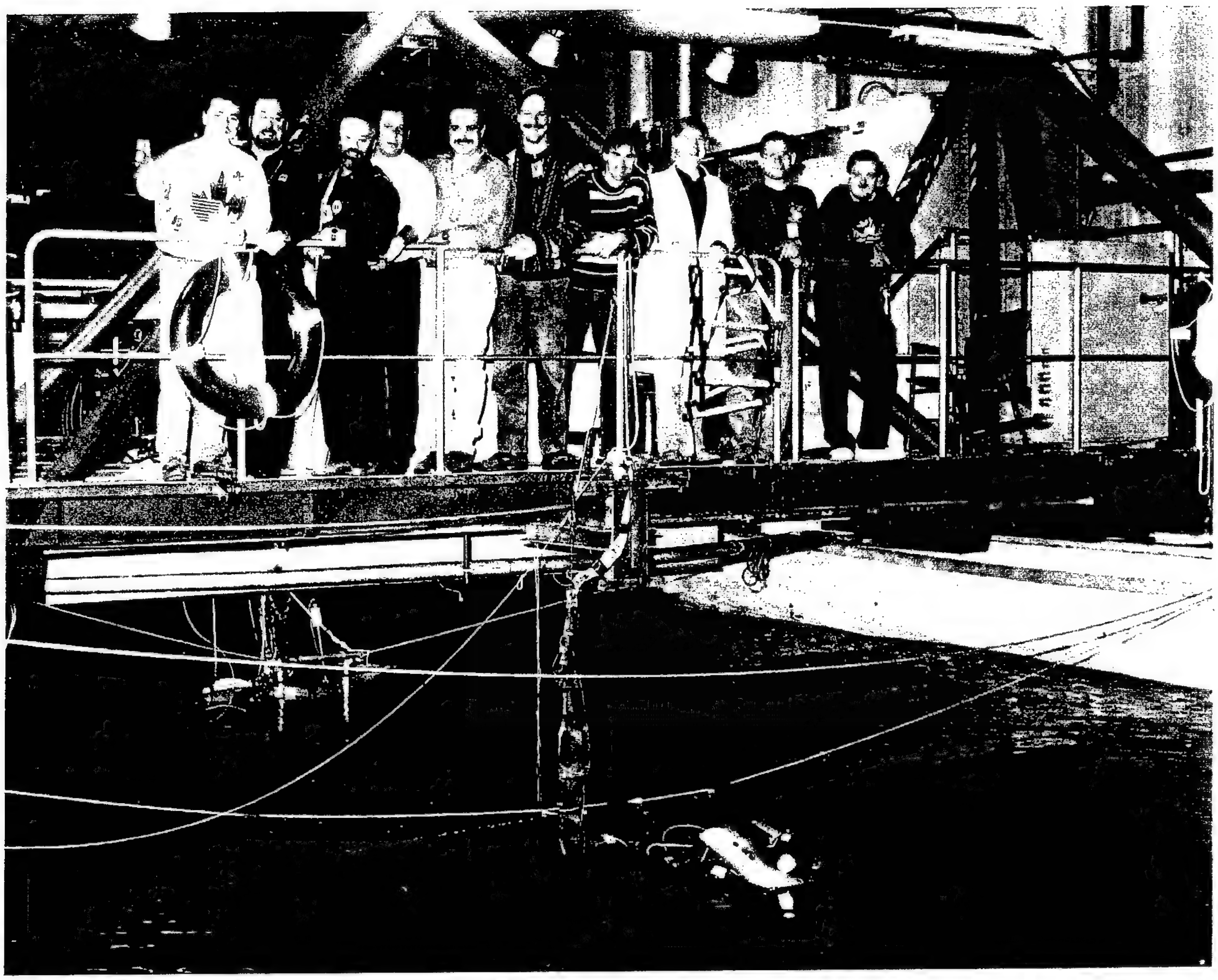

Figure 3. Picture showing the position of the human subject and the thermal manikin during the immersion tests relative to the towing tank carriage where the data were recorded.

Offshore North Sea Wave Project) wave spectrum for irregular waves was used for the tests to represent realistic ocean wave conditions. The wave period was selected to maximize the total wave energy (see McKenna and Simoes Ré, 1995).

An additional immersion test was performed in calm water (0 cm wave height) while the subjects and manikin were immersed up to the neck in a vertical posture (V0). For this condition, additional weight was fixed on the feet of the subjects to maintain the proper buoyancy. A single wave height was used per day, only one subject was tested at any time, and each subject was tested at the same time of the day. Each immersion continued for a maximum exposure of 60 minutes or until i) core temperature reached 35.0°C, ii) dizziness or nausea preclude further exposure, iii) the subject asked to be removed from the water or iv) the attending physician or investigator ended the exposure. Once the waves had stopped, the subjects were removed from the water and assisted onto the platform for a sitting period of two minutes to stabilize the blood pressure.

At the beginning of each experimental day, the dressed manikin was immersed in water up its neck to purge by hydrostatic pressure the trapped air from the inside of the suit through a flexible Tygon™ tube placed under the neck seal of the suit. This procedure was performed to allow consistency with previous protocols used by the CORD Group Limited for manikin testing, but was not performed on humans. For the human subjects, however, some of the trapped air was purged from the inside of the suit through the umbilical cord during the positioning of the subjects in water. For the testing sessions, the manikin was placed in the standard manikin immersion frame and positioned in the water. Buoyancy was added to the immersion frame until an anticipated survivor flotation position was achieved with the manikin assuming a slightly positive buoyant position. The immersion frame was then attached to the carriage with flexible tubing fixed at the four corners of the frame to maintain the same position relative to the wave propagation. The suit system remained on the manikin during the different trials performed for a specific wave condition.

To complement the immersion study, the insulation of the suit system was also measured in air at the same average air temperature as during the immersion tests (16.6°C). The suit insulation was measured in air on two subjects by following the same procedures as for the water immersion tests, except that the subjects were free standing in air for 1 hour and no air was expelled from the suit by hydrostatic pressure. In addition, the volume of the trapped air inside the immersion suit was measured on two subjects for the normal flotation position and for the vertical position in water. First the subject was normally dressed with the immersion suit system, and then the umbilical was sealed at the distal end to avoid any air leakage from the system. The subject was then immersed in water by following the same procedures as during an immersion test, and adopted the normal

flotation position or was immersed up to the neck. During each immersion, the volume of air expelled from the suit into the umbilical was measured. No measurement was performed in air for the manikin.

Statistical analysis. A two-factor (heat source [subject or manikin] and wave height) repeated-measures Analysis of Variance (ANOVA) was used to compare the suit insulation at steady-state during the trials (Abacus Concepts Inc., Berkeley, CA, 1989). A one-factor (wave height) MANOVA (multivariate ANOVA) was used to analyze differences in skin temperature, skin heat flux, heart rate and rectal temperature for the subjects' wave trials at steady-state. When a significant effect was found ($p < 0.05$), a Mean Contrast Test was used to locate significance between the means (using the Greenhouse-Geisser adjusted p-value). Where applicable, data are presented as mean ± SE. The level of statistical significance was set at $p < 0.05$, unless otherwise stated.

RESULTS

All the data presented in the present report are averages from the last 15 minutes of the 1 h immersion when thermal steady state was achieved. On average, the skin and suit components temperature values decreased by 0.18 ± 0.01 °C and the heat flux values by 1.98 ± 0.15°C W • m^{-2} over the last 15 minutes of the immersion for an average decrease of 1.5 ± 0.3% of the calculated insulation values. Leakage of water into the suit was detected only during human testing and on only two occasions over the 89 runs (54 immersions using human subjects and 35 immersions using the manikin). The leakages occurred through punctured umbilicals and were not sufficient to compromise the validity of the data.

On average, the water temperature was 15.95 ± 0.02°C and the air temperature 16.60 ± 0.31 °C during the trials and no differences in temperature were observed between wave conditions.

Buoyancy of the human subjects and manikin. A significant portion of the subject's body surface area was not in contact with the water during the immersion tests because of the 15.4 kg of buoyancy provided by the life vest in addition to the air trapped inside the immersion suit. It was estimated from analysis of the video recordings performed during the tests that about 30 to 40% of the subjects' body surface area was exposed to air during the water immersions. The body sites exposed to air during the tests were the forehead (almost 100% of the testing time in contact with air except for WH70 condition where occasional water splashes occurred), chest (85 ± 5% of the testing time in

contact with air), the front thigh (80 ± 7%), the forearm (79 ± 7%), the shin (67 ± 4%), the abdomen (51 ± 11%) and the shoulder (24 ± 6%; see Fig. 4). The proportion of time in air for those sites varied between subjects because of differences in anthropometry between subjects, and hence differences in suit fit. Note that the upper arm site, because of its location on the inner portion of the arm facing the side of the subject's trunk, could not be seen easily by the video camera and no firm conclusion could be reached regarding its location in or out the water during the immersion tests.

Because of the density of the manikin, extra buoyancy was added to the immersion frame until a simulated survivor flotation position was achieved with the manikin. It was estimated from the video recordings that only about 10 to 20% of manikin surface area was exposed to air during the water immersions. The body sites in air during the tests were the forehead (almost 100% of the testing time in contact with air except for tests above WH40 condition where occasional water splashes occurred), forearm (45 ± 11% of the testing time in contact with air), chest (33 ±9%), shoulder (24 ± 5%), and shin (3 ± 1%; see Fig. 4).

Physiological parameters for the human subjects. Heart rate (HR). On average *HR* increased significantly from 55 ± 3 beats • min^{-1} for the 0 cm wave condition (WH0) to 61 ± 4 beats • min^{-1} for the 0 cm wave condition in vertical position (V0). Although not a significant increase compared to 0 cm wave condition, *HR* increased to 59 ± 4 beats • min^{-1} for the 70 cm wave condition (WH70; see Fig. 5).

Rectal temperature (T_{re}). Tre decreased significantly during the hour of immersion by 0.24 ± 0.02°C from 37.31 ± 0.03 °C to an average of 37.07 ± 0.07 °C for the last 15 min of the immersion. T_{re}, however, was not affected by the wave conditions, averaging 37.16 ± 0.04 °C and 37.15 ± 0.04°C for the WH0 and WH70 conditions respectively.

Skin temperature (T_{sk}). Mean T_{sk} ($\overline{T}_{sk}$) was not affected by the wave conditions except for the VO condition where $\overline{T}_{sk}$ was 27.70 ± 0.53°C compared to an average of 29.83 ± 0.11°C for the other wave conditions. $\overline{T}_{sk}$ decreased on average by 0.82 ± 0.26°C during the hour of immersion in water; the largest decrease in T_{sk} was observed at the distal limbs, particularly at the forearm site (1.35 ± 0.21°C) and the smallest decrease was for the trunk, specifically at the abdomen site (0.01 ± 0.12 °C; see Fig. 6).

Mean skin heat flux($\overline{H}_{sk}$). $\overline{H}_{sk}$ was largest for the V0 condition (99.2 ± 3.4 W • m^{-2}) and smallest for the WH0 condition (72.0 ± 1.9 W • m^{-2}), being respectively significantly higher and lower than the other wave conditions. $\overline{H}_{sk}$, however, was not different between WH0 and WH10 conditions. $\overline{H}_{sk}$ was not different between WH20 and WH50 inclusively, but these values were significantly higher than WH0 and WH10, and lower than WH60 and WH70 (see Fig. 7). For a more detail analysis of the wave effect on

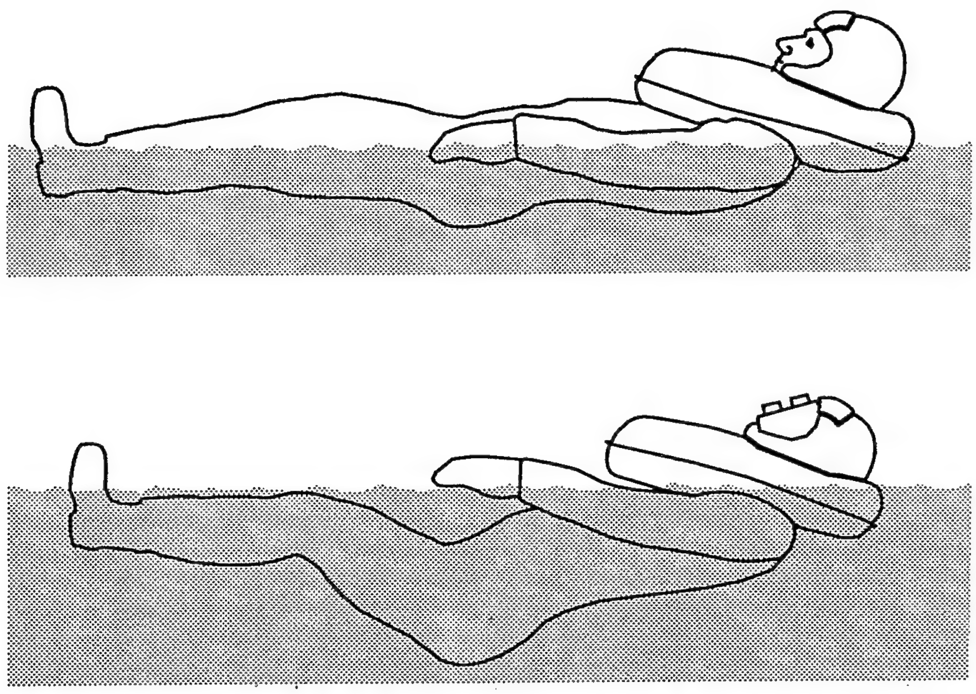

Figure 4. Drawings representing the typical buoyancy of a human subject (top) and of the thermal manikin (bottom) during water immersion at 0 cm wave height condition. The thermal manikin in shown here without the immersion frame.

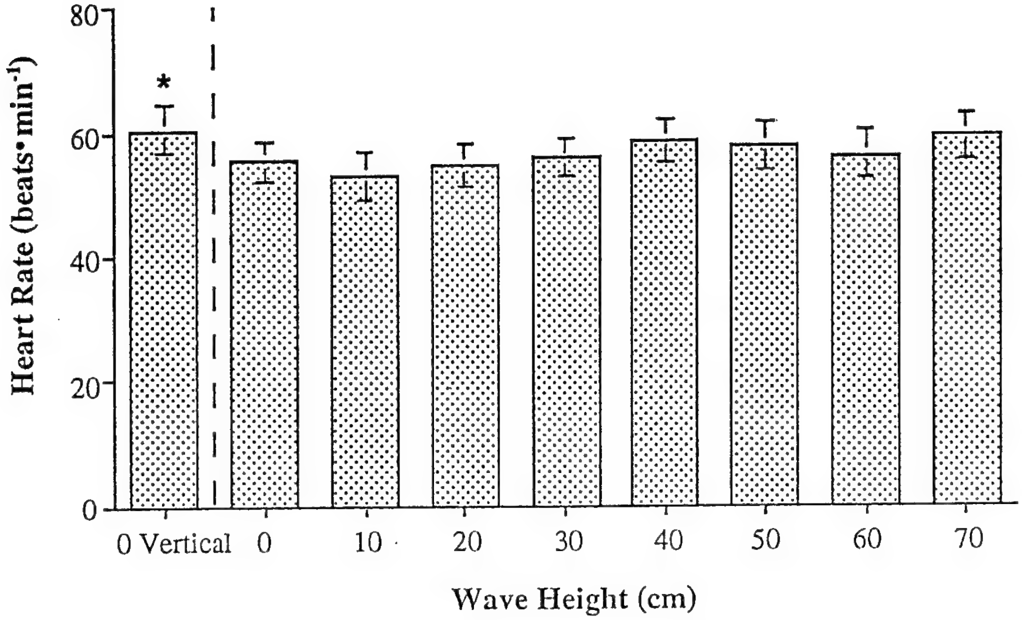

Figure 5. Effect of wave height and vertical immersion on subject's heart rate during immersion posture in 16°C water. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

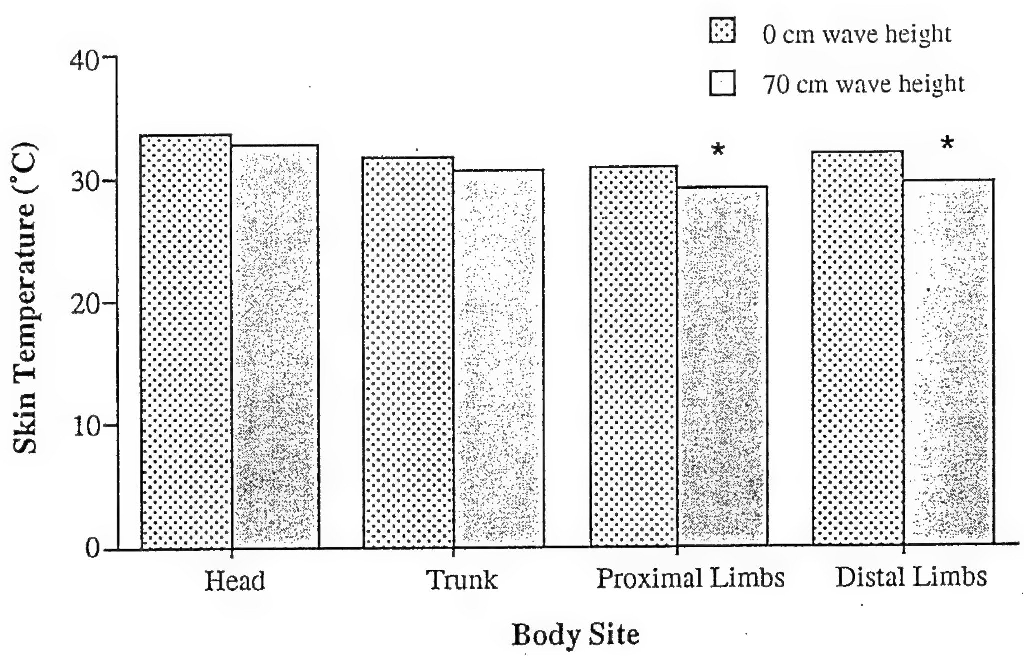

Figure 6. Effect of wave height and vertical immersion posture on subject's skin temperature during immersion in 16°C water. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

skin heat loss, the body was divided into four segments: the head which was defined by the forehead site, the trunk which comprises the chest, sub-scapula, abdomen and lower back sites, the proximal limbs which comprises the shoulder, upper arm, and the front and back thigh sites, and the distal limbs which comprises the forearm, shin and calf sites. From WH0 to WH70, the skin heat loss increased significantly for the head, trunk and proximal limbs by 71.1 ± 8.0, 14.5 ± 6.8 and 9.2 ± 4.2 W • m^{-2} respectively, while it did not changed significantly for the distal limbs (0.8 ± 6.1 W • m^{-2}; see Fig. 8).

Insulation of the system components for the human trials. Insulation of the pile garment(R_{pile}). The pile insulation includes the insulation of the pile garment in addition to the air layer which is between the skin of the subject and the pile layer. R_{pile} calculated for the V0 condition was significantly lower [0.58 ± 0.02 Clo (0.090 ± 0.003 m^2 • K • W^{-1})]] than for the other wave conditions, and no difference was found for conditions between WH0 and WH70 inclusively [average of 0.81 ± 0.03 Clo [0.126 ± 0.005 m^2 • K • W^{-1}; see Fig. 9].

Insulation of the suit (R_{suit}). The suit insulation includes the insulation of the suit in addition to the air layer which is comprise between the pile garment and the suit layer. R_{suit} calculated for V0 condition was significantly lower [0.18 ± 0.01 Clo (0.028 ± 0.002 m^2 • K • W^{-1})] than the other wave conditions, and no difference was observed for conditions between WH0 and WH70 inclusively [average of 0.32 ± 0.01 Clo (0.050 ± 0.002 m^2 • K • W^{-1}) ; see Fig. 10].

Insulation of the water/air ($R_{water/air}$). The insulation of the environment includes the air or water layer between the suit and the air or water sensors. R_{air} was measured for the forehead site since this site was always in air (except for occasional splashing at WH70), and R_{water} was measured for the other sites. $R_{water/air}$ was significantly higher for WH0 [0.24 ± 0.03 Clo (0.037 ± 0.005 m^2 • K • W^{-1})] and WH10 [0.17 ± 0.02 Clo (0.026 ± 0.003 m^2 • K • W^{-1})] and significantly lower for WH70 [0.06 ± 0.01 Clo (0.009 ± 0.002 m^2 • K • W^{-1})] compared to the other wave conditions. No difference was observed for conditions between WH20 and WH60 inclusively [average of 0.09 ± 0.01 Clo (0.014 ± 0.002 m^2 • K • W^{-1}); Fig. 11].

Total insulation of the suit system (R_{total}). R_{total} is the "in series" summation of R_{pile}, R_{suit} and $R_{water/air}$. R_{total} was significantly lower for V0 [0.85 ± 0.03 Clo (0.132 ± 0.005 m^2 • K • W^{-1})] compared to the other wave conditions. R_{total} did not change significantly for conditions between WH0 and WH50 inclusively [average of 1.28 ± 0.04 Clo (0.198 ± 0.006 m^2 • K • W^{-1})], except between WH0 [1.35 ± 0.03 Clo (0.209 ± 0.005 m^2 • K • W^{-1})] and WH30 [1.22 ± 0.03 Clo (0.189 ± 0.005 m^2 • K • W^{-1})] where R_{total} values are different. Values of R_{total} were not different between WH60 [1.16 ± 0.02

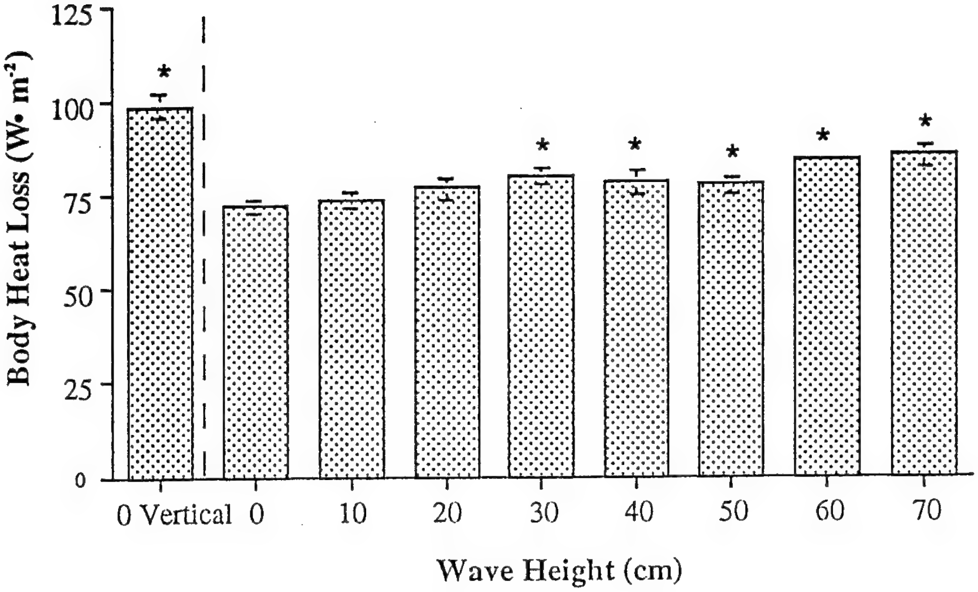

Figure 7. Effect of wave height and vertical immersion posture on subject's mean body heat flux during immersion in 16°C water. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

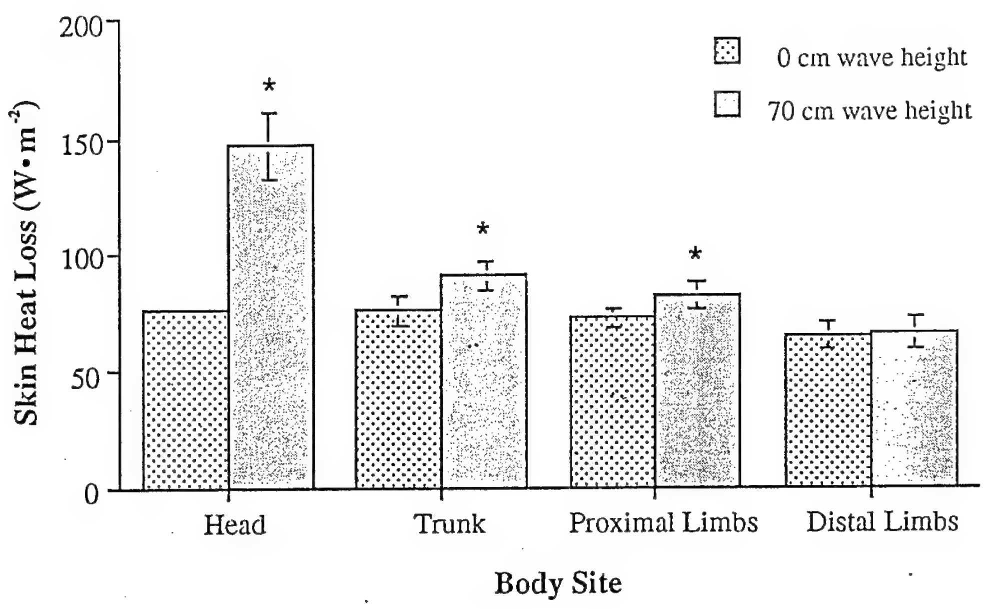

Figure 8. Skin heat flux from the head (forehead site), trunk (chest, sub-scapula, abdomen, and lower back sites), proximal limbs (shoulder, upper arm, front thigh, and back thigh sites) and distal limbs (forearm, shin, and calf sites) of the human subjects for 0 and 70 cm wave conditions. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

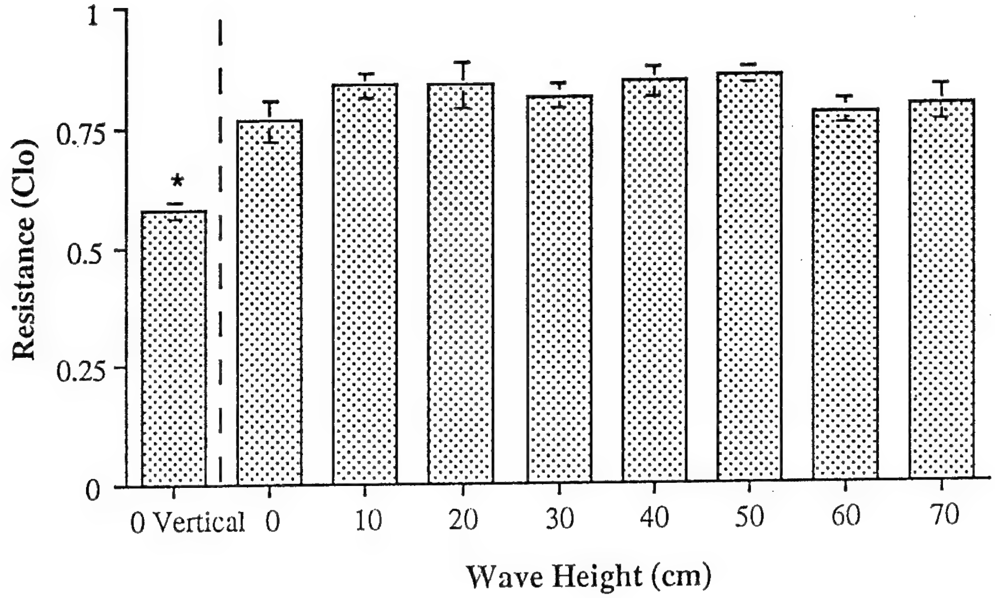

Figure 9. Effect of wave height and vertical immersion posture on the thermal resistance of the pile garment (R_{pile}) worn by the human subjects during immersion in 16°C water. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

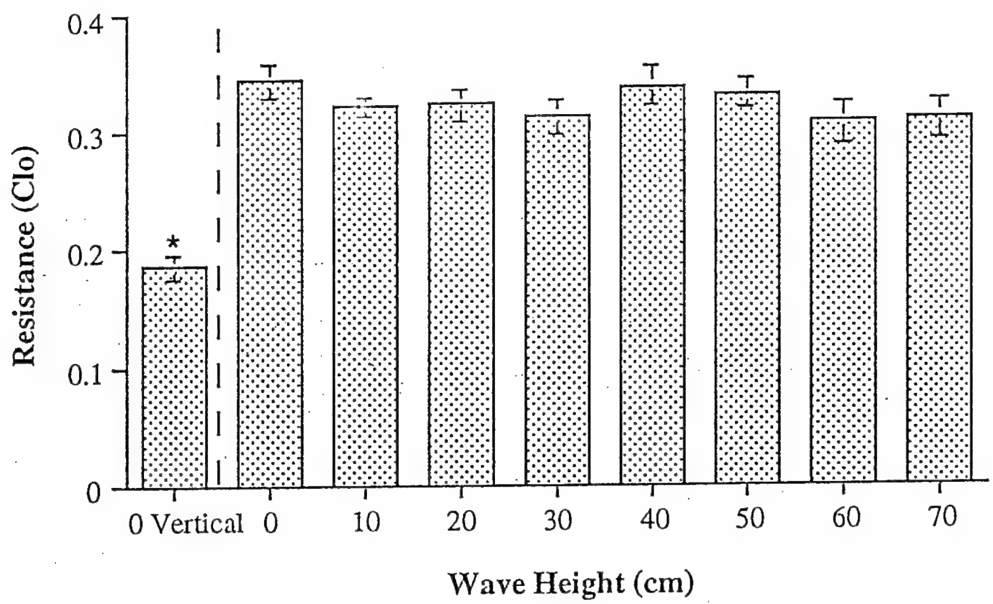

Figure 10. Effect of wave height and vertical immersion posture on the thermal resistance of the suit garment (R_{suit}) worn by the human subjects during immersion in 16°C water. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

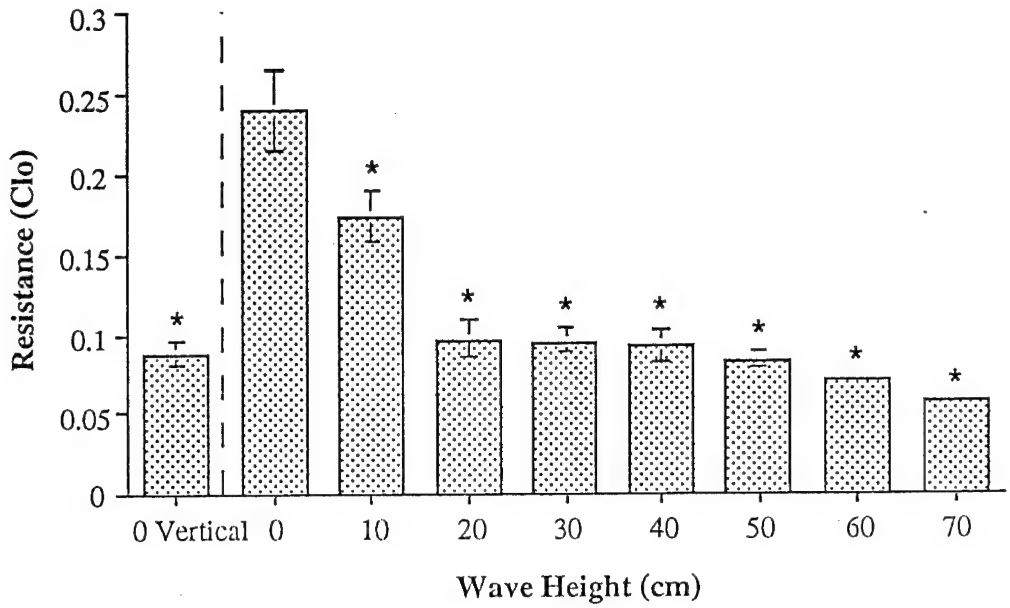

Figure 11. Effect of wave height and vertical immersion posture on the thermal resistance of the water or air ($R_{water/air}$) surrounding the human subjects during immersion in 16°C water. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

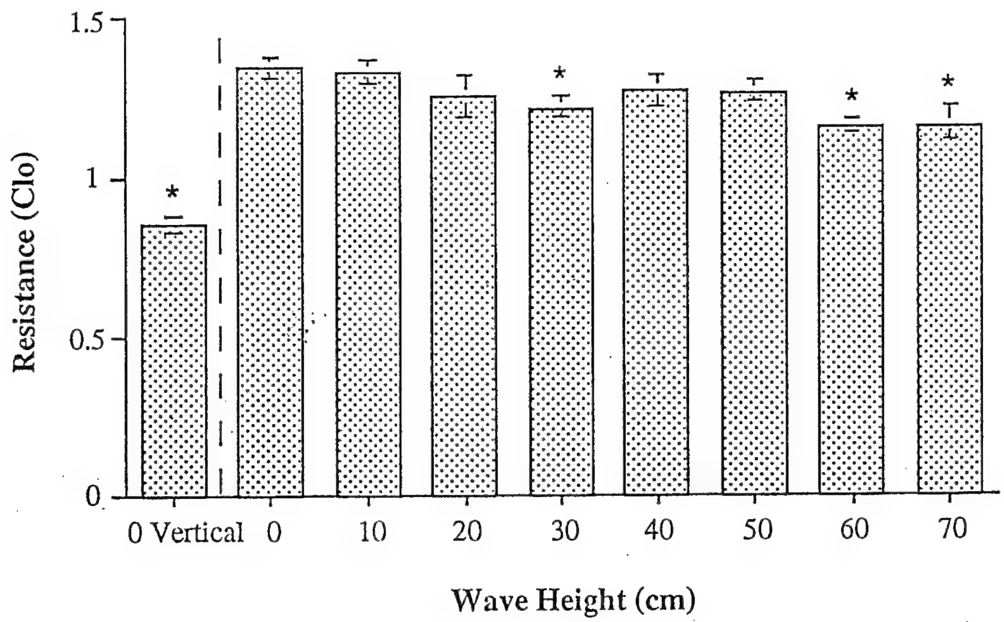

Figure 12. Effect of wave height and vertical immersion posture on the total thermal resistance (R_{total}) of the suit system ($R_{pile} + R_{suit} + R_{water/air}$) worn by the human subjects during immersion in 16°C water. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 wave height condition.

Clo (0.180 ± 0.003 m$^2 \cdot$ K $\cdot$ W^{-1})] and WH70 [1.16 ± 0.02 Clo (0.180 ± 0.003 m$^2 \cdot$ K $\cdot$ W^{-1})] conditions but these values were about 14% lower than R_{total} at WH0 [1.35 ± 0.03 Clo (0.209 ± 0.005 m$^2 \cdot$ K $\cdot$ W^{-1})] and WH10 [1.33 ± 0.04 Clo (0.206 ± 0.006 m$^2 \cdot$ K $\cdot$ W^{-1}); see Fig.12]. The total insulation of the suit system was most affected by the wave conditions for the head segment where R_{total} decreased by an average of 0.86 ± 0.06 Clo (0.133 ± 0.009 m$^2 \cdot$ K $\cdot$ W^{-1}) from WH0 to WH70 compared to the trunk and proximal limb segments where the decreases in R_{total} were 0.54 ± 0.13 Clo (0.084 ± 0.020 m$^2 \cdot$ K $\cdot$ W^{-1}) and 0.21 ± 0.09 Clo (0.033 ± 0.014 m$^2 \cdot$ K $\cdot$ W^{-1}), respectively. No significant change was observed in R_{total} between WH0 and WH70 for the distal limb segments [-0.05 ± 0.15 Clo (-0.008 ± 0.023 m$^2 \cdot$ K $\cdot$ W^{-1}); see Fig. 13].

Separating the subject's body surface area for sites under (sub-scapula, lower back, back thigh and calf sites) and above the water (forehead, chest, forearm, front thigh, shin, abdomen, and shoulder sites) during the immersion tests shows that on average the total thermal resistance of the suit system for the sites outside the water was 42% higher than for the sites inside the water (see Fig. 14). The difference between the sites disappeared during the vertical posture test because all the sites were in contact with the water (in water sites: 0.79 ± 0.10 Clo (0.122 ± 0.016 m$^2 \cdot$ K $\cdot$ W^{-1}); "out of water" sites: 0.86 ± 0.03 Clo (0.133 ± 0.005 m$^2 \cdot$ K $\cdot$ W^{-1}); see Fig. 14). Note that for the V0 condition the forehead site was not used in the present analysis because it stayed in contact with air. Furthermore, Fig. 14 shows that the wave conditions (WH0 compared to WH70 condition) and the hydrostatic pressure (WH0 compared to V0 condition) decreased the thermal resistance of the suit system more for the sites outside the water (wave conditions: 25.2% decrement; hydrostatic pressure: 55.4% decrement) than for the sites inside the water (wave conditions: 8.0% decrement; hydrostatic pressure: 17.9% decrement). Again, the forehead site was not used to calculate the effect of the hydrostatic pressure on the thermal resistance of the suit system.

Mean manikin heat loss ($\overline{H}_{sk}$). $\overline{H}_{sk}$ for the manikin increased significantly from WH0 (71.8 ± 3.7 W $\cdot$ m^{-2}) to WH70 condition (84.1 ± 0.7 W $\cdot$ m^{-2}). $\overline{H}_{sk}$ observed for the V0 condition (76.8 ± 0.9 W $\cdot$ m^{-2}) was higher than WH0 but lower than the other wave conditions (see Fig. 15). When the manikin was divided into four segments (head, trunk, proximal and distal limbs), heat loss increased significantly from WH0 to WH70 for the head, trunk and proximal limbs by 9.5 ± 1.3, 13.1 ± 8.0 and 28.2 ± 6.6 W $\cdot$ m^{-2} respectively, while it did not significantly change for the distal limbs (2.0 ± 16.5 W $\cdot$ m^{-2}; see Fig. 16).

Insulation of the system components for the manikin trials. Insulation of the pile garment (R_{pile}). R_{pile} calculated for the V0 condition [0.32 ± 0.02 Clo (0.050 ± 0.003 m^2

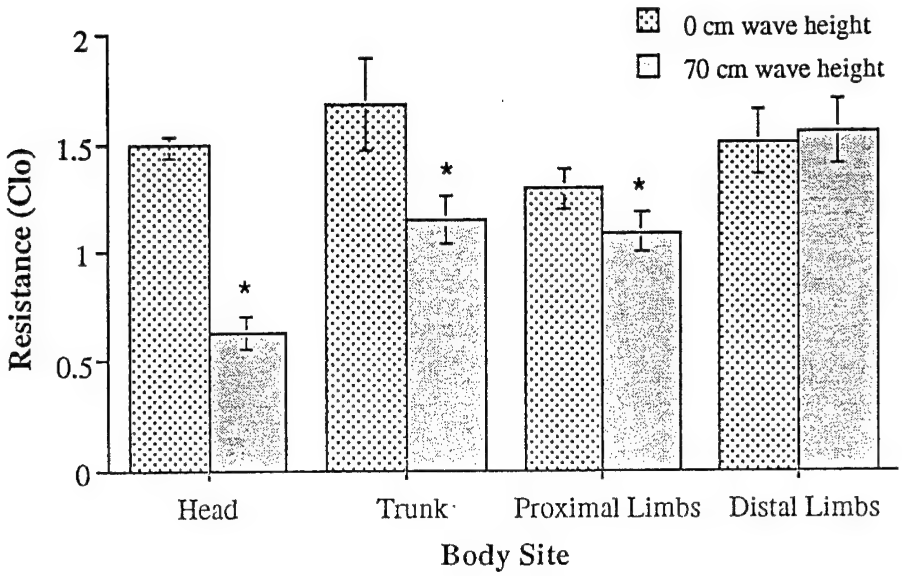

Figure 13. Total thermal resistance (R_{total}) of the suit system ($R_{pile} + R_{suit} + R_{water/air}$) for the head (forehead site), trunk (chest, sub-scapula, abdomen, and lower back sites), proximal limbs (shoulder, upper arm, front thigh, and back thigh sites) and distal limbs (forearm, shin, and calf sites) of the human subjects for 0 and 70 cm wave conditions. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

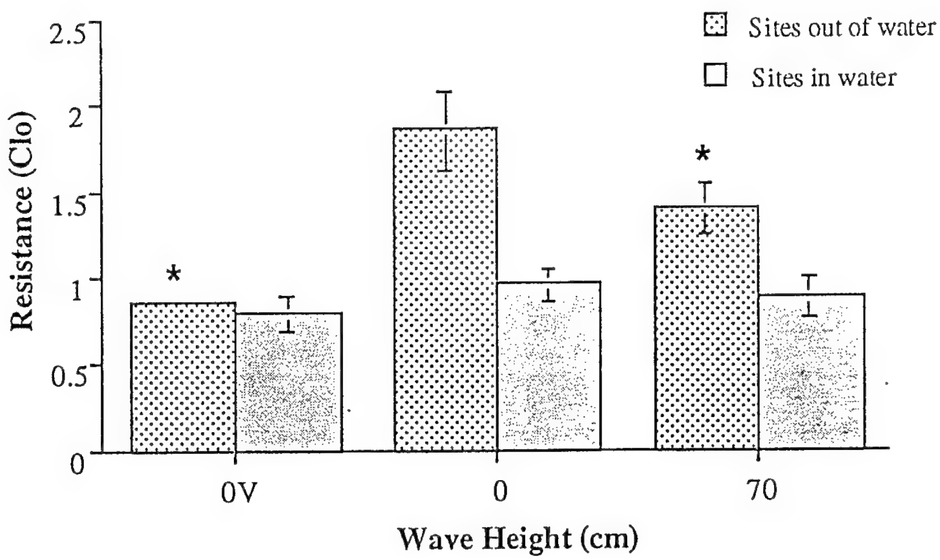

Figure 14. Total thermal resistance (R_{total}) of the suit system worn by human subjects ($R_{pile} + R_{suit} + R_{water/air}$) for the sites in water (sub-scapula, lower back, back thigh and calf) and partly outside the water (forehead, chest, forearm, front thigh, shin, abdomen and shoulder) for 0 and 70 cm wave heights and vertical immersion posture conditions. n = 6. Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

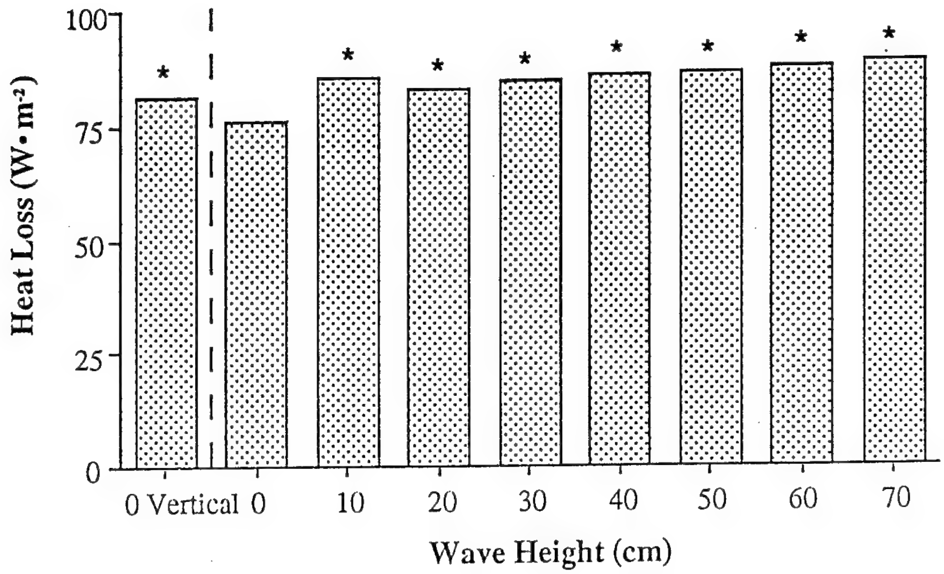

Figure 15. Effect of wave height and vertical immersion posture on manikin mean body heat loss during immersion in 16°C water. n = 4 (number of trials on the same manikin). Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

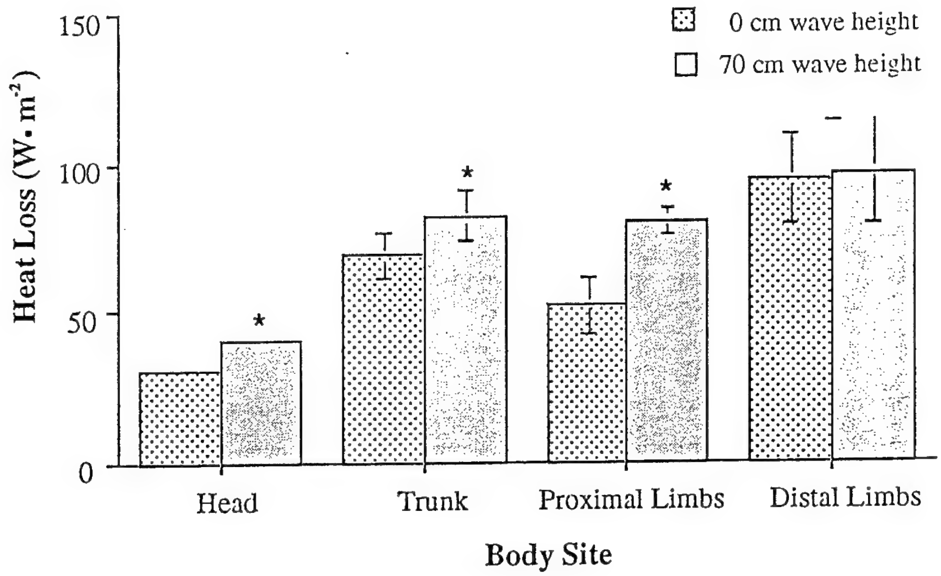

Figure 16. Skin heat flux from the head (forehead site), trunk (chest, sub-scapula, abdomen, and lower back sites), proximal limbs (shoulder, upper arm, front thigh, and back thigh sites) and distal limbs (forearm, shin, and calf sites) of the manikin for 0 and 70 cm wave conditions. n = 4 (number of trials on the same manikin). Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

$\bullet$ K $\bullet$ W^{-1})] was significantly lower than the other wave conditions, and R_{pile} at WH0 [0.51 ± 0.00 Clo (0.079 ± 0.000 m^2 $\bullet$ K $\bullet$ W^{-1})] was significantly higher than the other wave conditions (see Fig. 17). Every wave condition was significantly different from each others but no general trend was observed with the increase of wave height.

Insulation of the suit (R_{suit}). R_{suit} calculated for the V0 condition [0.031 ± 0.002 m^2 $\bullet$ K $\bullet$ W^{-1}) was significantly higher than WH0, 20, 30, 60 and 70, and lower than WH10, 40 and 50 conditions. R_{suit} for the WH0 condition [0.18 ± 0.01 Clo (0.028 ± 0.002 m^2 $\bullet$ K $\bullet$ W^{-1})] was significantly higher than for the WH20, 30 and 60 conditions, and lower than for WH10, 40 and 50 conditions. No general trend in R_{suit} was observed with the increased wave height (see Fig. 18).

Insulation of the water/air ($R_{water/air}$). $R_{water/air}$ calculated for the V0 [0.08 ± 0.00 Clo (0.012 ± 0.00 m^2 $\bullet$ K $\bullet$ W^{-1})] and WH0 [0.11 ± 0.00 Clo (0.017 ± 0.000 m^2 $\bullet$ K $\bullet$ W^{-1})] conditions were significantly different from each other and higher than for any other wave conditions. In general $R_{water/air}$ tended to decrease with an increase in wave height although a plateau was observed between WH20 and 60 (see Fig. 19).

Total insulation of the suit system (R_{total}). R_{total} calculated for V0 [0.60 ± 0.01 Clo (0.093 ± 0.002 m^2 $\bullet$ K $\bullet$ W^{-1})] and WH0 [0.79 ± 0.00 Clo (0.122 ± 0.000 m^2 $\bullet$ K $\bullet$ W^{-1})] conditions were respectively significantly lower and higher than the other wave conditions (see Fig. 20). A significant decrease of 0.14 Clo (0.022 m^2 $\bullet$ K $\bullet$ W^{-1}; 17.2%) in R_{total} was observed between WH0 and WH70 wave conditions. The total insulation of the suit system was most affected by the wave conditions for the proximal limbs where R_{total} decreased by an average of 1.17 ± 0.22 Clo (0.181 ± 0.034 m^2 $\bullet$ K $\bullet$ W^{-1}) from WH0 to WH70 compared to the trunk and head where the decrease in R_{total} was respectively 0.30 ± 0.20 Clo (0.047 ± 0.0.31 m^2 $\bullet$ K $\bullet$ W^{-1}) and 0.19 ± 0.11 Clo (0.029 ± 0.017 m^2 $\bullet$ K $\bullet$ W^{-1}). No significant change was observed in R_{total} between WH0 and WH70 for the distal limbs [-0.34 ± 0.32 Clo (-0.053 ± 0.050 m^2 $\bullet$ K $\bullet$ W^{-1}); see Fig. 21].

R_{total} values calculated for the manikin' suit system by the CORD Group Limited using the temperature sensors imbedded into the manikin' skin and the manikin power sources are reported in Fig. 20 for comparison purpose (CORD Group Limited, 1994). Because the manikin sites used for the measurement of heat loss, skin and suit system temperatures were not exactly the same between the CORD Group system and ours (see *Material and Methods*), and because water temperature was used for every sites in the calculation of resistances whathever the sites were above or below water, a more valid comparison between our resistance data and CORD Group data can be achieved by correcting the CORD Group data to make it equivalent to the DCIEM measurement system (see *Material and Methods* for details in correction method). The new CORD Group values

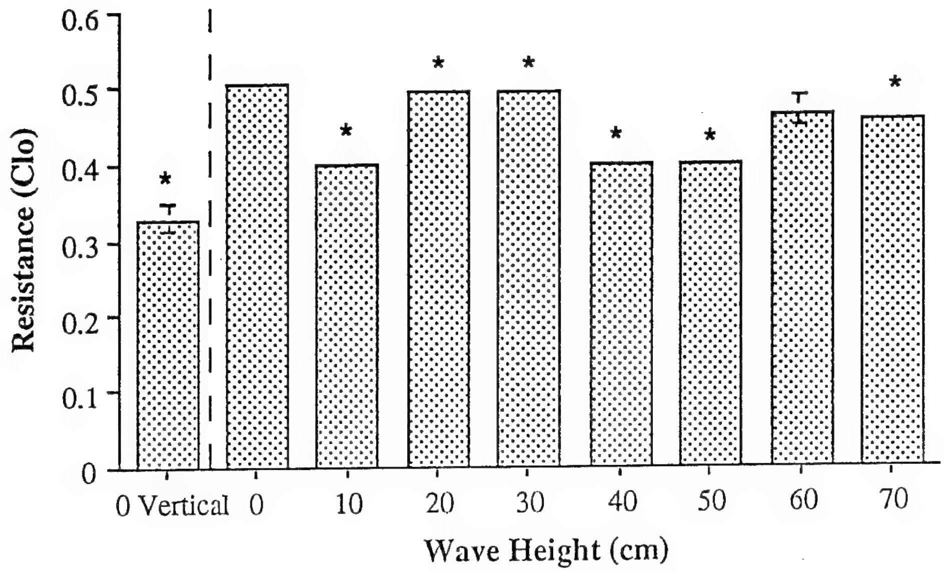

Figure 17. Effect of wave height and vertical immersion posture on the thermal resistance of the pile garment (R_{pile}) worn by the manikin during immersion in 16°C water. n = 4 (number of trials on the same manikin). Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

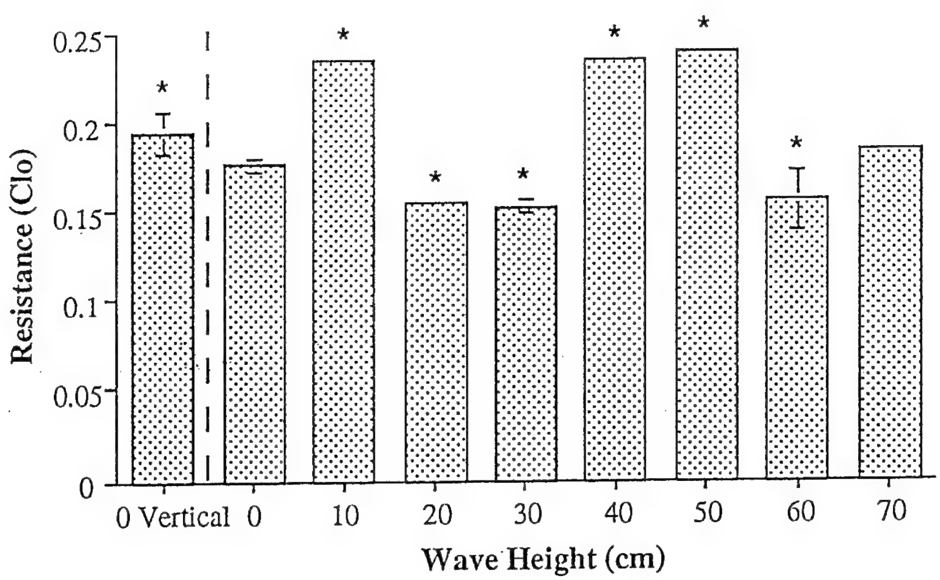

Figure 18. Effect of wave height and vertical immersion posture on the thermal resistance of the suit garment (R_{suit}) worn by the manikin during immersion in 16°C water. n = 4 (number of trials on the same manikin). Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

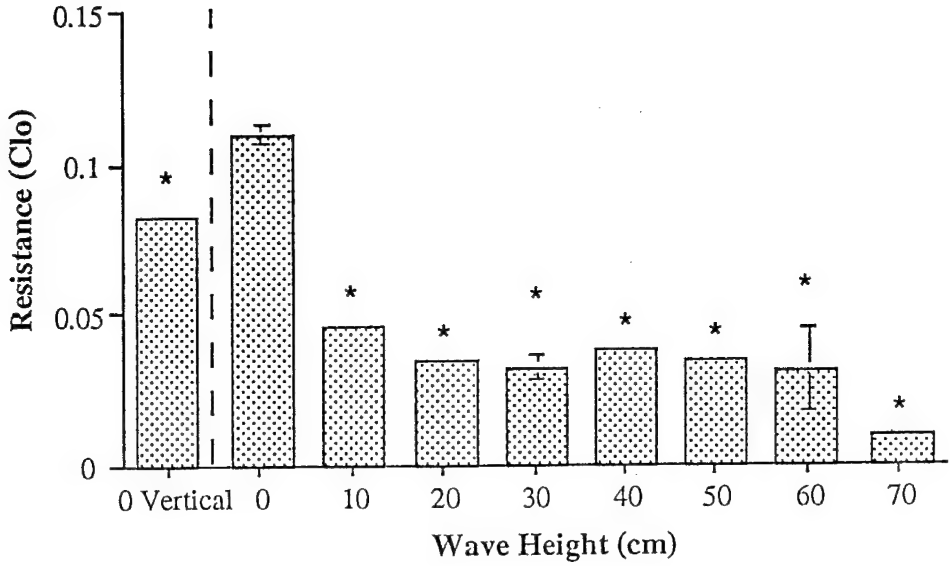

Figure 19. Effect of wave height and vertical immersion posture on the thermal resistance of the water and air ($R_{water/air}$) surrounding the manikin during immersion in 16°C water. n = 4 (number of trials on the same manikin). Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

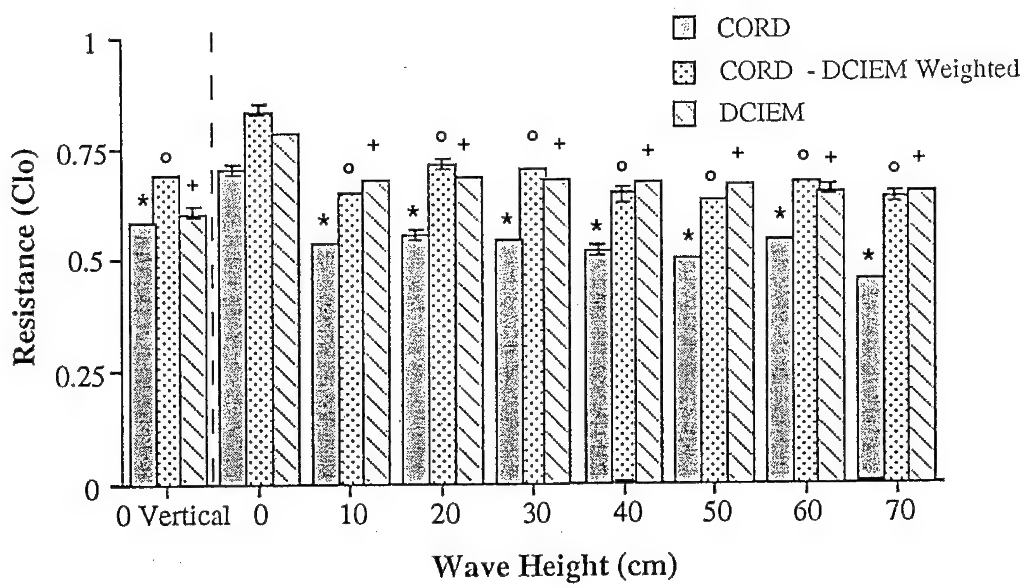

Figure 20. Effect of wave height and vertical immersion posture on the total thermal resistance (R_{total}) of the suit system ($R_{pile} + R_{suit} + R_{water/air}$) worn by the manikin during immersion in 16°C water. CORD: R_{total} calculated by CORD Group Limited; CORD-DCIEM weighted: CORD data corrected for DCIEM sensors' location; DCIEM: R_{total} calculated using DCIEM sensors. n = 4 (number of trials on the same manikin). Data represents means ± SE. *, 0, +: significantly different ($p < 0.05$) from the 0 cm wave height condition for the CORD, CORD - DCIEM weighted and DCIEM data, respectively.

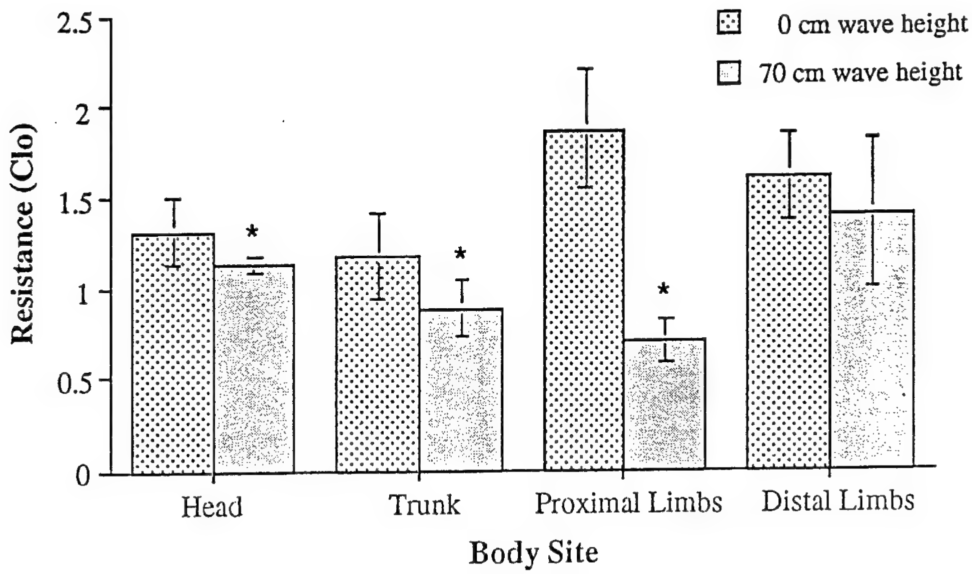

Figure 21. Total thermal resistance (R_{total}) of the suit system ($R_{pile} + R_{suit} + R_{water/air}$) for the head (forehead site), trunk (chest, sub-scapula, abdomen, lower back sites), proximal limbs (shoulder, upper arm, front thigh, back thigh sites) and distal limbs (forearm, shin, calf sites) of the manikin for 0 and 70 cm wave conditions. n = 4 (number of trials on the same manikin). Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

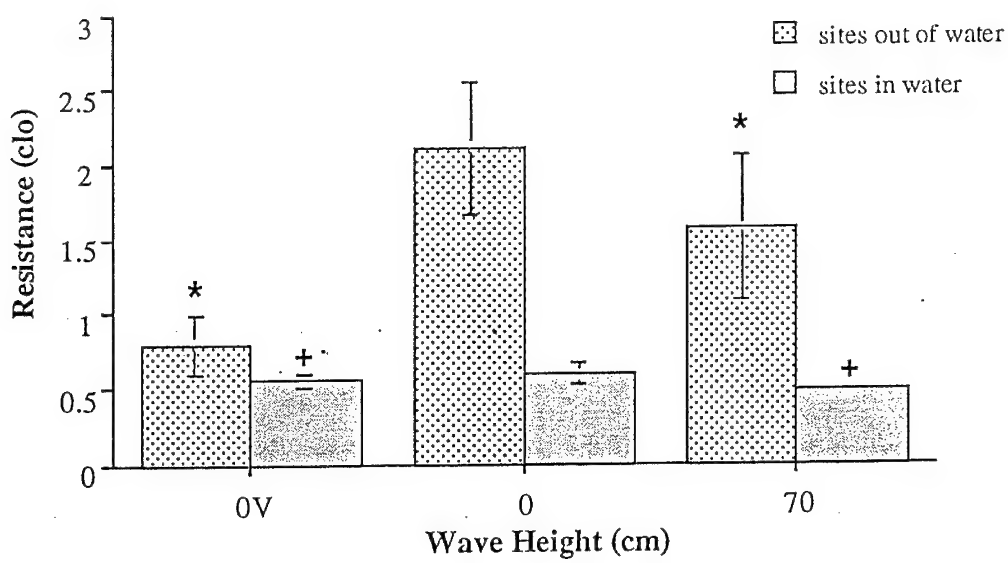

Figure 22. Total thermal resistance (R_{total}) of the suit system worn by the manikin ($R_{pile} + R_{suit} + R_{water/air}$) for the sites in water (sub-scapula, lower back, back thigh and calf) and partly outside the water (forehead, shoulder, chest, forearm and shin) for 0 and 70 cm wave heights and vertical immersion posture conditions. n = 4 (number of trials on the same manikin). Data represents means ± SE. *: significantly different ($p < 0.05$) from the 0 cm wave height condition.

for R_{total}, called R_{total} *CORD-DCIEM weighted*, are much closer to the R_{total} values measured in the present study (5% difference on average; see Fig. 20) as compared to the original R_{total} values provided by the CORD Group (21% difference on average). This suggests that two independant measuring systems, one using total power to the manikin and another using HFTs, can provide similar resistance results if the differences between the two measuring systems are accounted for.

Dividing the manikin's body surface area for sites inside (sub-scapula, lower back, back thigh and calf sites) and outside the water (chest, shoulder, forearm, and shin sites) during the immersion tests shows that on average R_{total} for the sites outside the water was 70% higher than for the sites inside the water. The difference between the sites disappeared during the vertical posture test because all the sites were in contact with the water ("in water" sites: 0.56 ± 0.05 Clo (0.087 ± 0.008 $m^2 \cdot K \cdot W^{-1}$); "out of water" sites: 0.79 ± 0.19 Clo (0.122 ± 0.029 $m^2 \cdot K \cdot W^{-1}$); see Fig. 21). Furthermore, Fig. 22 shows that the wave motion (WH0 compared to WH70 condition) and the hydrostatic pressure (WH0 compared to V0 condition) decreased more the thermal resistance of the suit system for the sites outside the water (wave motion: 25.4% decrement; hydrostatic pressure: 62.0% decrement) than for the sites inside the water (wave motion: 10.2% decrement; hydrostatic pressure: 6.6% decrement).

Insulation of the immersion suit system during the air trials. The average R_{pile} calculated during the air trial for two subjects [0.83 ± 0.11 Clo (0.129 ± 0.017 $m^2 \cdot K \cdot W^{-1}$)] was not different from the R_{pile} observed during the immersion trials (0.81 ± 0.03 Clo). R_{suit} during the air trials was on average twice as much as the R_{suit} values calculated for the immersion trials, and R_{air} during the air trials was about 3.5 times larger than $R_{water/air}$ during the immersion trials. This results in a R_{total} value during the air trials [2.10 ± 0.03 Clo (0.326 ± 0.005 $m^2 \cdot K \cdot W^{-1}$)] significantly higher than the R_{total} values obtained during the immersion trials at WH0 [1.28 ± 0.04 Clo (0.198 ± 0.006 $m^2 \cdot K \cdot W^{-1}$)] and V0 [0.85 ± 0.03 Clo (0.132 ± 0.005 $m^2 \cdot K \cdot W^{-1}$)].

Volume of trapped air inside the immersion suit system. The average total volume of trapped air measured inside the suit system for the two subjects was 25.9 ±1.4 L (24.5 and 27.3 L), and the average volume of trapped air inside the suit during normal flotation position was 17.5 ± 2.9 L (14.6 and 20.4 L). This means that an average of 67.2 ± 7.5 % of the total trapped air normally inside the suit system when standing in air was expelled out of the suit through the umbilical during the immersion tests.

DISCUSSION

R_{total} during human and manikin testing. The results of the present study confirm our hypothesis that the total thermal resistance of dry immersion suit is decreased during wave motion as compared to still water, for both humans and manikin. The total thermal resistance of the dry suit system decreased by 14 and 17% for human and manikin, respectively, from still water condition to 70 cm wave height. This is, to our knowledge, the first study reporting on the effect of standardized wave height on the thermal resistance of dry immersion suits using humans as subjects. Previous studies testing dry suits were mainly performed on a thermal manikin and reported a decrement in suit thermal resistance between 25-30% for 60 cm wave height (Sowood et al., 1994) and 36% for 70 cm wave height condition (CORD Group Limited, 1994) for the same suit system as the present study. Those figures are 1.5 to 2.6 times larger than the decrement observed in the present study for both humans and manikin. Steinman et al. (1987) studied the effect of non-controlled wave conditions on the thermal performance of anti-exposure garments worn by humans, and showed for dry suits that heart rate is elevated in rough water compared to calm water condition, but no differences were observed for rectal temperature cooling rates and the declines in skin temperatures. Unfortunately, suit insulation was not calculated. Those results are in agreement with the present study where heart rate had a tendency to increase ($p < 0.08$), but rectal temperature cooling rates and skin temperatures were not affected by the wave conditions despite a significant increase of the skin heat flux with wave height. Other studies investigating the effect of wave motion on suit insulation were performed on wet suits where it was shown that leakage and flushing inside immersion suits could be responsible for a significant decrease in suit insulation between immersion in calm versus moving water. Romet et al. (1991) reported an average decrement of the thermal resistance of eleven wet suits of 30% and 56% for humans and manikin, respectively, from still water to water made turbulent with 25 - 40 cm wave amplitude. The decrement in wet suit insulation reported in the Romet et al. study is twice as much compared to the decrement observed in the present study for dry suits tested on humans and more than three times larger than the value observed on a manikin. This is probably attributed to leakage and flushing of water into the wet suits which was not present during the present dry suit testing. This is confirmed by the study of Steinman et al. (1987) which reported that wet suits allowed significantly greater rectal temperature cooling rate and larger declines in skin temperature in rough water than in calm water when compared to dry suits. Steinman et al. (1987) were able to positively correlate these changes with subjective evaluations of cold water flushing during the immersion tests. From the studies of Hall

and Polte (1956) and Allan et al. (1985), it is now well established that leakage of water inside a wet suit significantly decreases the effective insulation of immersion suits.

Effects of wave motion on the thermal resistance of the suit system components. At least three factors could have contributed to the reduction of the insulation provided by a dry suit during wave motion: leakage of water into the suit, compression of the suit insulation by the wave motion, and reduction of the water and air boundary layers due to water movement. The first two factors affect the insulating layers inside the suit, while the last factor affects the insulating layer of the water or air surrounding the suit. In the present study, only the last two factors could contribute to a reduction of the suit system insulation during wave motion since the suits did not leak. Sowood et al. (1994) suggested that part of the decrement observed in suit thermal resistance could be attributed to the effect of the water movement over the manikin surface. The results from the present study support this assumption and our hypothesis that a major factor responsible for the decrease in suit system insulation during wave motion is the decrease of $R_{water/air}$, the insulating boundary layer surrounding the suit. In fact, our study shows that $R_{water/air}$ was the only suit system component that was significantly affected by the wave motion, and that the major portion of the $R_{water/air}$ decrease occurred at wave height below 20 cm. R_{pile} and R_{suit} were not significantly reduced by the wave motion as shown in figs. 6 and 7. This supports the observation of Hayes et al. (1985) who reported that the deleterious effect of waves appears to be more demonstrable when the subjects are nude or wearing little clothing, probably because the reduction of the boundary layer has more impact when it is the major portion of the system insulation. These results suggest that the compression of the internal suit insulating layers by the wave motions was not sufficient to have an impact on the amount of air trapped inside the insulating layers of the suit during tests on human subjects.

Effects of wave motion on the thermal resistance of the different body sites. To define which parts of the immersion suit had their thermal resistance most affected by the wave motion, the human and manikin bodies were divided in four segments: the head, trunk, proximal limbs and distal limbs (see *Material and Methods* for details). The extremities, namely the hands and feet, were excluded from the analyses because being vasoconstricted during cold water immersion, they will only play a marginal role in survival. The results for humans showed that the 70 cm wave condition increased vasoconstriction (a further decrease in T_{sk} compared to the WH0 condition) only at the limb sites (proximal and distal). This minimized the increase of the skin heat loss for the proximal limbs and abolished it for the distal limbs during wave motion (see Fig. 6). On the other hand, because of the weak vasoconstriction capacity of the skin of the head (see Fig. 4), head heat loss doubled from WH0 to WH70 condition, mainly due to water

splashing occurring during wave breaks at WH70, while trunk heat loss increased by 20%. These changes were mainly responsible for the observed 58% and 32% decrement in suit thermal resistance at the head and trunk, respectively, for the WH70 compared to the WH0 condition. Meanwhile, for the same wave conditions, suit thermal resistance decreased by only 16% for the proximal limbs and did not changed significantly for the distal limbs. These tests suggest that to minimize body heat loss and body cooling during water immersion, further development of dry immersion suits should focus on improving the thermal protection at the head and trunk, and not at the limbs. As reported by Romet et al. (1991), the results are different for wet suits where a significant increase in heat flow was only observed at the back site which was the most affected by water flushing and pooling during water immersion. The wave conditions during the Romet et al. study (1991) were not sufficient to cause the waves to break over the heads of the subjects, and this could account for the absence of a significant increase in head heat loss.

Since the skin temperature of the manikin was maintained constant during the immersion tests, only heat loss could vary due to wave motion. The largest increase in heat loss from condition WH0 to WH70 was observed at the proximal limbs of the manikin (54% increase). This indicated a decrease of 63% in the thermal resistance of the suit system at the proximal limb sites. Although not as acute, changes of 25 and 14% were observed for the thermal resistance of the suit system at the trunk and head sites of the manikin during wave motions. This contrasts with the results obtained during human testing where the head was the most affected by the wave motions. Like the human testing, however, the thermal resistance of the suit system at the distal limbs when measured on the manikin was not affected by the wave motion. These findings only partially support previous studies which reported for dry suits that the largest decrement in suit insulation was observed for the head, chest, back, hand and legs of the manikin (Sowood et al., 1994). These results differ from wet suit testing where Romet et al. (1991) reported that insulation of the suit system at the arm and abdomen sites of the manikin was the most affected by wave motion. Differences observed between humans and manikin can reflect differences in buoyancy and interaction with waves between the two bodies during water immersion.

Comparison between human and manikin testing. Because the same suit system was tested on one manikin without removing it between immersion trials, the fit of the suit system was constant between trials. This condition was different when compared to the human trials where six different subjects, having different anthropometric characteristics and thus different fits, were tested with the same suit system as for the manikin trials. Different fits means different quantities of trapped air inside the suit for the different

subjects, and therefore, different buoyancy. This became evident during the analyses of the video recording of the immersion trials where differences in buoyancy were observed between subjects. Ultimately, different buoyancy will translate into different thermal resistance for the suit system because the ratio of body surface area below and above the water is not constant. This difference in fit, therefore, was probably largely responsible for the larger variability observed for the resistance values obtained during the human trials when compared to the manikin trials (about 10 times larger). Because of the tighter results obtained from the manikin, some resistance values became significantly different between wave conditions without showing any general trend or "physiological significance" for survival time. This was the case for example for R_{pile} and R_{suit} values calculated from the manikin trials where differences as small as 0.03 Clo (0.005 $m^2 \bullet K \bullet W^{-1}$) between wave height conditions became significantly different, but no general trend was observed for the suit system insulation from WH0 to WH70 conditions (see Figs. 15 and 16).

Despite a similar effect of wave motion on suit system insulation between human subjects and manikin (14 and 17% decrement for humans and manikin, respectively), the thermal resistance values were on average 46% lower when measured on the manikin [R_{total} from 0.78 to 0.65 Clo (0.121 to 0.101 $m^2 \bullet K \bullet W^{-1}$)] compared to human subjects [R_{total} from 1.35 to 1.16 Clo (0.209 to 0.180 $m^2 \bullet K \bullet W^{-1}$)] for the same water conditions (WH0 to WH70) and suit system. The discrepancy may largely be explained by the difference in buoyancy and amount of trapped air in the suit between the manikin and human subjects.

Hall et al. (1956) reported that the insulation value of an immersion suit will decrease by a factor of 2.3 times when measured in water [1.45 Clo (0.225 $m^2 \bullet K \bullet W^{-1}$)]; immersion up to the neck without leakage of water into the suit) compared to air [3.36 Clo (0.521 $m^2 \bullet K \bullet W^{-1}$)]. In the present study, we observed a decrease of R_{total} by a factor of 2.5 times between the air trials and the VO condition during the immersion trials. They attributed the effect to water compression (hydrostatic pressure) which reduced the trapped air in the insulation layers of the suit, and to the elimination of the boundary air layer and its replacement by water with higher thermal conductivity. In the present study, the larger portion of the human's body surface area exposed to air during the immersion trials (30 to 40%) probably contributed in providing, for the same reasons, a larger overall suit system insulation when compared to the 10 to 20% surface area in contact with air in the case of the manikin.

The second factor contributing to the larger insulation values of the suit system when measured on humans is the larger amount of air trapped inside the insulating layers of the suit worn by the human subjects. This was the consequence of purging all the air out

of the manikin suit before the trials (see *Material and Methods* for details), a procedure which was not performed for the human subjects. For the human subjects, however, the air was partially expelled out of the suit through the umbilical cord during the positioning of the subjects in water. Despite this, it was found that about 8 L of trapped air was still present inside the suit system of the human subjects during the immersion tests. The air purge procedure was not performed on humans to simulate as closely as possible accidental immersion in water where trapped air is normally not intentionally removed from a dry suit. Because of methodological limitations associated with data recording (the wires from the probes had to exit the suit), however, about 67% of the air normally trapped into a dry suit was lost and this could have been responsible for lower thermal resistance values for the suit system as compared to real accidental immersion conditions. The remaining trapped air inside the immersion suit was also partly responsible for the better buoyancy of the human subjects.

Differences in buoyancy between human subjects and the manikin had a further impact on the suit system insulation measured on the manikin by allowing more water splashing and, therefore, increasing convective heat loss during wave motion as compared to human trials. Analysis of the trial's video recordings revealed that because of the high buoyancy provided by the dry suit with trapped air, the flexible humans were floating like corks on water, going along and in phase with the wave motion. This minimized the splashing and water movement relative to the non-immersed portions of the suit, which consequently minimized the heat transfer from the suit and maintained high suit insulation. In contrast, the heavy manikin was made buoyant in water by adjusting the air content in the two buoyancy lobes attached on each side of the immersion frame fixed to the manikin. Although this arrangement helped to simulate an anticipated survivor floatation position, the manikin buoyancy and its interaction with the wave movement was not the same as for the human subjects. A large portion of the surface area of the manikin was awashed in water and instead of going perfectly along with the wave movement, the rigid manikin and frame system was partly out of phase with the wave propagation because of its inertia; the response time was damped by the immersion frame and the weight of the manikin. The inertia of the manikin system carried it deeper into the trough of the waves, and this induced the waves to break on the manikin's body, causing water splashes which increased convective and evaporative heat transfer from the suit. These factors contributed to decrease the overall suit system insulation when measured on the manikin. This supports the observations made by Light et al. (1987) that the flotation angle (buoyancy) of an immersed victim is crucial not only in terms of wave riding and the maintenance of airway freeboard, but also in terms of heat transfer and survival time.

To better understand the effect of different buoyancy and amount of trapped air between humans and manikin on R_{total} values, trials were performed where both humans and manikin were immersed in water up to their neck in a vertical posture without waves (V0 condition). To achieve this posture, weights were added to the subject's ankles and the amount of air in the life vest was adjusted until a similar posture compared to the manikin was achieved. During the V0 condition, all parts of the humans' and the manikin's bodies, except for the head, were in contact with water, and the hydrostatic pressure should have expelled most of the trapped air from inside the suits. These conditions should have eliminated all differences in buoyancy and in the amount of trapped air between human subjects and the manikin. The results showed that indeed, R_{total} decreased by 37% [from 1.346 to 0.848 Clo (0.209 to 0.131 $m^2 \cdot K \cdot W^{-1}$)] and 23% [from 0.782 to 0.601Clo (0.121 to 0.093 $m^2 \cdot K \cdot W^{-1}$)] for humans and the manikin, respectively, during the V0 trials as compared to the W0 trials. The decrement in R_{total} was 61% larger (37% compared to 23%) on humans than on the manikin because of the better buoyancy and larger amount of air trapped in the suit during the human trials. Despite similar buoyancy conditions during the V0 trials, the differences in R_{total} values between the human subjects and the manikin decreased only from an average of 46% for the W0 to Wh70 conditions to 29% for the V0 condition. This suggests that factors other than buoyancy and trapped air can be responsible for differences between R_{total} measured on humans and a manikin. Such factors can be the differences in the fit of the suit between humans and the manikin, differences in the distribution of skin temperature which was uniform on the manikin but heterogeneous on humans, or differences in heat fluxes. We observed in the present study that for the V0 condition R_{total} values varied by more than 20% between subjects, from 0.74 Clo (0.115 $m^2 \cdot K \cdot W^{-1}$) for the thinner subject with 11% body fat and a $\overline{H}_{sk}$ of 117 $W \cdot m^{-2}$, to 0.89 Clo (0.138 $m^2 \cdot K \cdot W^{-1}$) for the fattest subject with 22% body fat and a $\overline{H}_{sk}$ of 94 $W \cdot m^{-2}$. This suggests that fit and/or skin temperature and heat flux differences can affect R_{total} of the suit in V0 condition. Further studies are necessary to clarify the impact of these factors on the differences between human and manikin trials.

Comparison with R_{total} reported by the CORD Group Limited for the manikin. R_{total} was calculated for the dry suit immersion system of the manikin by the CORD Group by using, as parameters, the manikin skin temperature provided by the imbedded skin temperature probes, water temperature and the power provided to the different heaters of the manikin's segments to keep its skin constant at 25°C. The CORD Group reported that R_{total} for the same suit system and the same conditions decreased by 36% from 0.70 Clo (0.109 $m^2 \cdot K \cdot W^{-1}$) at WH0 to 0:45 Clo (0.069 $m^2 \cdot K \cdot W^{-1}$) at WH70 (CORD Group

Limited, 1994).. This contrasts with the 14 and 17% decrement observed in the present study for humans and the manikin, respectively. Furthermore, the R_{total} values reported by CORD Group [from 0.70 to 0.45 Clo (0.109 to 0.069 $m^2 \cdot K \cdot W^{-1}$)] were on average 21% lower than the values calculated for the manikin in the present study [from 0.78 to 0.65 Clo (0.121 to 0.101 $m^2 \cdot K \cdot W^{-1}$)] for WH0 to WH70 conditions.

Two factors might have contributed to this discrepancy: the use of the extremities in the calculation of the suit insulation, and the use of T_{water} for the calculation of R_{total} for every site on the manikin. As mentioned previously, the extremities were excluded from the insulation analysis in the present study because of the lack of relevance with survival, but this was not the case for the analysis performed by the CORD Group. The following equation was used by the CORD Group to calculate R_{total}:

$$R_{total} = SA \cdot \Delta\overline{T} / P_{total}$$

where SA is the total surface of the manikin (1.736 m^2), $\Delta\overline{T}$ is the average weighted manikin skin temperature during the trial (in °C) and P_{total} is the total power used to maintain the skin of the manikin constant at 25°C (in W). This equation assumes that all segments of the manikin are equivalent relative to their heat loss per square meter of surface area and that they will react to the same magnitude to wave motion. This assumption, however, is not supported by the large ratio of power / SA for the hands of the manikin (158.6 $W \cdot m^{-2}$ on average) compared to the ratio for the rest of the body (77.2 $W \cdot m^{-2}$ on average; CORD Group Limited, 1994). Consequently, the heat loss from the hands was more affected by the wave motions when compared to the rest of the body as shown by a 2.8 times increase of the ratio power / SA for the hands (158.6 to 601.4 $W \cdot m^{-2}$) as compared to the 33% increase of the ratio for the body (excluding the hands; 77.2 to 102.3 $W \cdot m^{-2}$) from WH0 to WH70 condition. This effect will not be present in humans since the extremities vasoconstrict during cold water immersion. This vasoconstriction in human extremities decreases skin heat loss, and will severely damp any effect that the wave motion might have on the suit insulation at those sites. When measured on a manikin, however, because the skin temperature is maintained constant, any effect of wave motion will increase heat loss and this effect will be accentuated by the large curvature effect of the extremities. This will exaggerate the effect of wave motion on suit insulation for the manikin as compared to humans in addition to decreasing the overall R_{total} measured on the manikin. To better understand the impact of an heterogeneous ratio of power / SA distribution over the body, take the extreme example of a thermal manikin exposed to cold water and dressed with a 1.5 Clo (0.233 $m^2 \cdot K \cdot W^{-1}$) garment over the trunk and limbs,

but with bared extremities. Since the skin temperature of the manikin is maintained constant over the whole manikin at 25°C, a very large portion of the power provided to the manikin will be lost through the extremities which act as heat dissipators. This will result in a very low garment insulation for the whole manikin, despite a large insulation over more than 80% of the manikin surface area. By removing the extremities from the manikin analyses (no power provided to the manikin extremities, which corresponds to vasoconstricted extremities on humans), the measured garment insulation will reflect more closely the real insulation of the garment covering the trunk and limbs.

A second factor that will affect R_{total} values is the use of T_{water} in the calculation of the thermal resistance for every site on the manikin, independent of whether the manikin site is below or above the water.

When the R_{total} values reported by CORD Group (CORD Group Limited, 1994) were corrected for the effect of those two factors (by removing the extremities in the calculation of R_{total} and using the proper ambient temperature), the new R_{total} values, called *CORD-DCIEM weighted*, increased by an average of 25%. In addition, the effect of the wave motion on R_{total} decreased to become closer to what is reported in the present study for the manikin (21% decrease of R_{total} from WH0 to WH70 condition for the *CORD-DCIEM weighted* values as compared to 17% for the present study and 36% for the CORD Group values). R_{total} calculated from the present study was on average 5% different compared to R_{total} CORD-DCIEM weighted values. This can be explained by the different locations of the temperature probes on the manikin between the present set-up and the CORD Group one, in addition to the limitation of a pin-point determination of the heat flux for a non-uniform system.. On a suit system where trapped air is uniformly expelled, and hydrostatic pressure is applied all around the body of the manikin (V0 condition), the location of probes on the body will probably not have a significant effect on the calculation of R_{total}. If, however, trapped air is not uniformly distributed around the body of the manikin and some body parts are in contact with air while others are inside water (WH0 to WH70 conditions), then location of the sensors on the body of the manikin will probably have a greater impact on the calculation of R_{total}.

To appreciate the practical implication of the differences in R_{total} values reported for the same suit system between the manikin and the human subjects, a survival mathematical model (Tikuisis, 1995) was used to estimate the survival time of a victim wearing the same suit system, having the same average anthropometric characteristics as in the present study, and immersed in cold water at 3°C with 70 cm wave height. Based on the R_{total} reported by the CORD Group Limited for the manikin [0.45 Clo ($0.070\ m^2 \cdot K \cdot W^{-1}$)], the victim would have died after only 8.6 hours of exposure to the cold water. From the present

study (see *RESULTS* and Fig. 23), a suit system insulation of 0.65 Clo (0.101 $m^2 \bullet K \bullet W^{-1}$) and 1.16 Clo (0.180 $m^2 \bullet K \bullet W^{-1}$), as measured on the manikin and human subjects, respectively, would have allowed the victim to survive 15.9 and over 40 hours for the same water conditions. This supports the observation of Romet et al. (1991) that when comparing human to manikin testing of immersion suits, greater effective insulation will result from human testing, which errs to the benefit of the humans. In the present study, the benefit for the humans translates into a three to five fold increase in survival time, depending on the method used to estimate R_{total}.

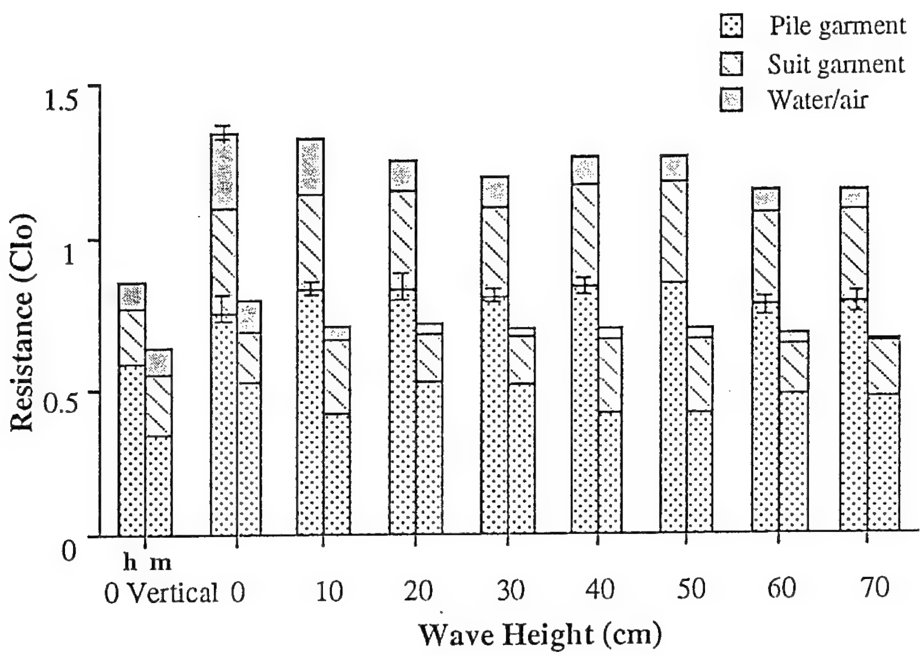

Figure 23. Effect of wave height and vertical immersion posture on the thermal resistance of the suit system components (R_{pile}, R_{suit}, and $R_{water/air}$) worn by the human subjects (h) and the manikin (m) during immersion in 16°C water. n = 4 (number of trials on the same manikin). Data represents means ± SE.

The use of a thermal manikin to test the thermal value of immersion suits has several practical advantages over the use of humans. Manikin testing can reduce the suit evaluation period, eliminate the ethical concerns, broaden the testing conditions since a manikin has no physiological limitations, and eventually decrease the cost of testing. Butin order to improve the correlation between human and manikin data, the next generation manikin must take into account the buoyancy of the human.

The results of the present study are limited to wave heights of up to 70 cm because of the mechanical limitations of the wave generator at the Institute for Marine Dynamics. It is expected, however, that rougher water conditions might further decrease the suit system

thermal resistance by reducing the thermal resistance of the air boundary layer of the sites that were not fully immersed during the present trials (mainly at the head), and by increasing the chances of leakage of water into the dry suit. Further studies, ideally performed in open ocean, are required to answer those questions.

In conclusion, the present study shows that wave heights up to 70 cm will decrease dry suit system insulation by 14 and 17% when measured on human subjects and a manikin, respectively, and that the only suit component significantly affected by the wave motion is the insulation of the water and air boundary layers surrounding the body. The body sites that were the most affected by the effect of wave motion were the head, and the proximal limbs with a 58% and 63% decrement in suit thermal resistance from 0 to 70 cm wave height for humans and manikin, respectively. Total suit insulation values were on average 46% lower when measured on manikin compared to human subjects for the same water conditions (WH0 to WH70) and suit system. The discrepancy may largely be explained by differences in buoyancy and amount of trapped air in the suit between the manikin and human subjects.

RECOMMENDATIONS

Based on the results of the present study, it is recommended to:

1. adjust existing and future mathematical models predicting survival time during water immersion for the effect of wave motion on immersion suit insulation;

2. improve the flotation characteristics of the thermal manikins to reflect more closely the flotation of the human body in water;

3. adjust the international standards for manikin testing to reflect more closely the thermal physiology of humans, particularly at the extremities; and

4. investigate the effect of higher wave heights on the insulation of immersion suits in open ocean conditions.

5. Do not purge the air out of the ensemble in manikin tests so that the data may be more easily compared with human subjects.

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APPENDIX

The thermal resistance of the suit system for the whole body can be calculated from its 12 parallel segments as follows:

$1 / R_t = H_t / \Delta T_t$

where R_t is the thermal resistance for the whole body (°C • m^2 • W^{-1}), H_t is the average heat flux from the body (W • m^{-2}) and ΔT_t is the average temperature difference between the body and the environment (°C). Knowing that

$H = Q / A$, and

$Q_t = \Sigma\, Q_i = \Sigma\, ([\Delta T_i \bullet A_i] / R_i)$, then

$$1 / R_t = Q_t / [A_t \cdot \Delta T_t] = (1 / [A_t \cdot \Delta T_t]) \sum Q_i = (1 / [A_t \cdot \Delta T_t]) \sum ([\Delta T_i \cdot A_i] / R_i)$$
$$= 1 / \Delta T_t \cdot \sum ([\Delta T_i / R_i] \cdot [A_i / A_t])$$

where Q_t is the average heat loss from the body (W), Q_i is the heat loss from segment i (W), ΔT_i is the temperature difference between the body and the environment for the segment i (°C), A_t and A_i are the surface areas for the body and the segment i, respectively, and R_i is the thermal resistance of the segment i ($W \cdot m^{-2}$). If the temperature is uniform on the body, then $\Delta T_t = \Delta T_i$ and

$$1 / R_t = \sum 1 / R_i \cdot \partial_i$$

where ∂_i is the weighting factor for segment i which correspond to the ratio A_i / A_t. If the skin temperature is not uniform on the body, then

$$1 / R_t = 1 / \sum ([\Delta T_i \cdot A_i] / A_t) \cdot \sum ([\Delta T_i / R_i] \cdot [A_i / A_t])$$
$$= \sum ([\Delta T_i \cdot A_i] / R_i) / \sum (\Delta T_i \cdot A_i)$$
$$= \sum (H_i \cdot \partial_i) / (\Delta T_i \cdot \partial_i)$$

therefore:

$$R_t = \sum (\Delta T_i \cdot \partial_i) / (H_i \cdot \partial_i)$$

where H_i is the heat loss from the segment i of the body ($W \cdot m^{-2}$).

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The objective of the present study was to investigate the effect of standard wave conditions (0 to 70 cm) on dry immersion suit insulation when tested on humans and manikin simultaneously. Six human subjects and a thermal manikin dressed with the same dry immersion suit system (pile undergarment insulation, uninsulated immersion suit and neoprene gloves and hood) were immersed simultaneously for one hour in 16°C water rendered turbulent with irregular wave pattern. One immersion was performed for each randomly chosen wave condition, from 0 to 70 cm wave height, changing by step of 10 cm. In addition to the physiological parameters measured on the human subjects (skin and rectal temperatures, skin heat loss and heart rate), and the ambient temperature of water and air, heat fluxes and surface temperatures were measured at 12 sites on the subjects and manikin for each compartment of the dry suit system (skin, pile garment, suit garment). This allowed the calculation of the thermal resistance of every suit compartment in addition to the air and water boundary layer surrounding the suit. The results showed that none of the physiological parameters were significantly affected by the wave conditions, except for the skin heat flux which increased with wave height from 72.0 ± 1.9 W • m^{-2} at 0 cm to 85.5 ± 2.9 W • m^{-2} at 70 cm. The thermal resistance data showed that wave height up to 70 cm decreased dry suit system insulation by 14 and 17% when measured on human subjects and manikin, respectively, and that the only suit component significantly affected by the wave motion was the insulation of the water and air boundary layers surrounding the body. The body sites that were the most affected by the effect of wave motion was the head, and the proximal limbs with a 58% and 63% decrement in suit thermal resistance from 0 to 70 cm wave height for humans and manikin, respectively. Total suit insulation values were on average 46% lower when measured on manikin (average of 0.68 ± 0.01 Clo) compared to human subjects (average of 1.25 ± 0.03 Clo) for the same water conditions and suit system. The discrepancy can largely be explained by differences in buoyancy and amount of trapped air into the suit between the manikin and human subjects.

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Thermal manikin, thermal resistance, immersion suit, insulation, wave height

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